New States Above Charm Threshold

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Fermilab

- New Narrow States
- QCD Dynamics Near Threshold
- X(3872), Z(3930), X(3943), Y(3940), Y(4260), Y(4350)
- Issues and Opportunities

(with K. Lane and C. Quigg)

New Narrow States

- ✓ Heavy-Light mesons:

  Chiral symmetry and HQS

  Coupling to decay channels

$D_s(2317)$	$J^P = 0^+$	$\mathrm{BaBar}(2003)$
$D_s(2460)$	$J^P = 1^+$	$\mathrm{CLEO}(2003)$
$\ldots$		(2006)

- ✓ Quarkonium states below threshold:

equal masses:	$h_c(3425)$	CLEO, E835 (2005)
	$\eta_c'(3638)$	Belle (2002)
unequal masses:	$B_c(6276)$	CDF (2006)

- ✓ Thresholds and the X,Y,Z states:

Quarkonium Systems

Potential models:

masses
spin splittings
EM transitions
hadronic transitions
direct decays

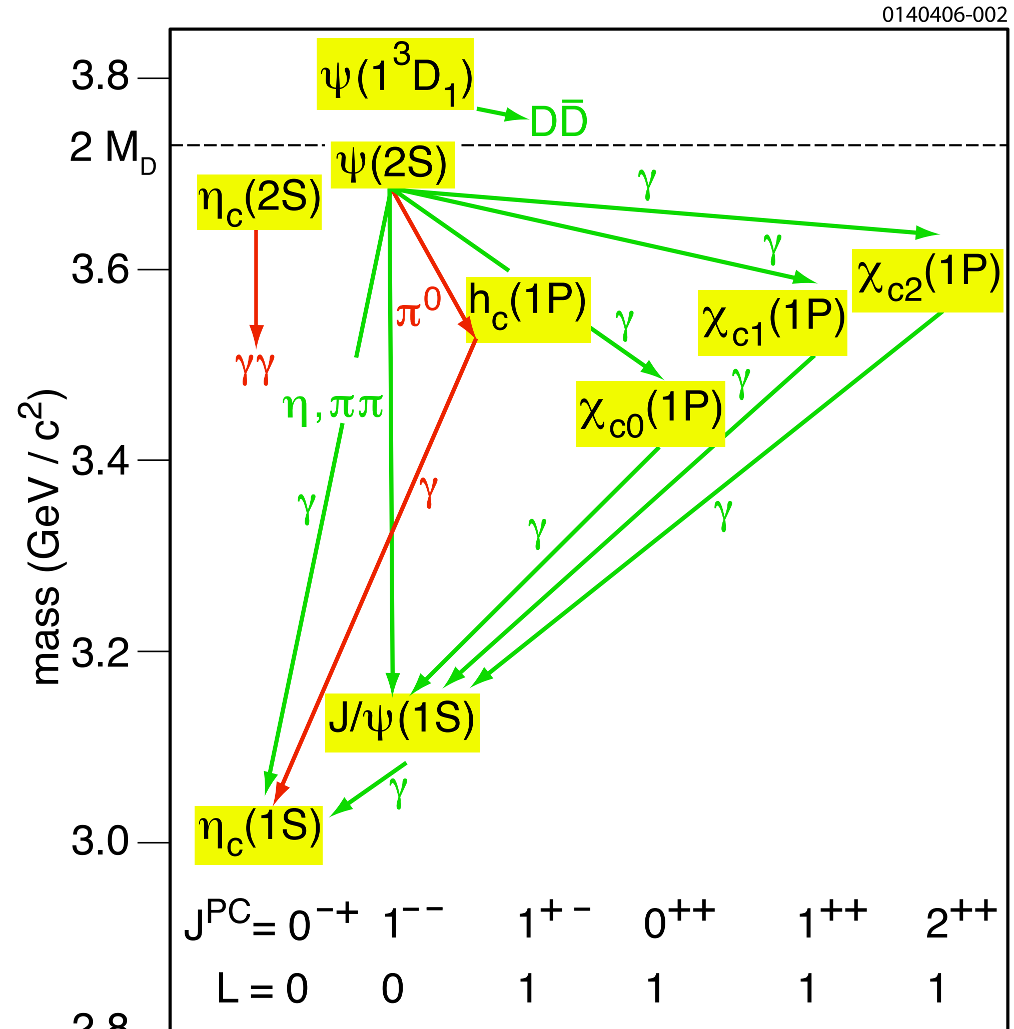


FIGURE 8. Transitions among low-lying charmonium states. From Ref. [65].

Lattice QCD:

masses
spin splittings
EM transitions

variety of approaches

Heavy quark potential

To $O(1/m^2)$

$$V(r) = V^{(0)}(r) + \left(\frac{1}{m_1} + \frac{1}{m_1}\right) V^{(1)}(r) + O\left(\frac{1}{m^2}\right)$$

$$+ \left(\frac{\vec{s}_1\,\vec{l}_1}{2m_1^2} - \frac{\vec{s}_2\,\vec{l}_2}{2m_2^2}\right)\left(\frac{V^{(0)}(r)'}{r} + 2\frac{V^{(1)}(r)'}{r}\right) + \left(\frac{\vec{s}_2\,\vec{l}_1}{2m_1m_2} - \frac{\vec{s}_1\,\vec{l}_2}{2m_1m_2}\right)\frac{V^{(2)}(r)'}{r}$$

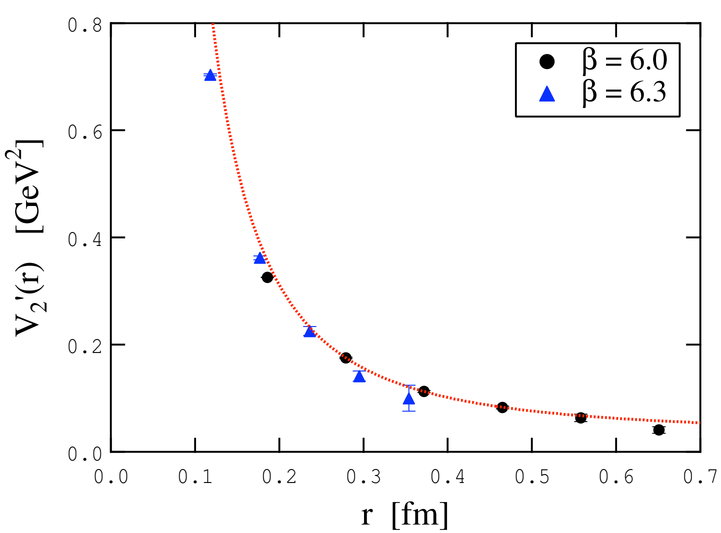
$$+\frac{1}{m_1m_2}\left(\frac{(\vec{s}_1\,\vec{r})\,(\vec{s}_2\,\vec{r})}{r^2} - \frac{\vec{s}_1\,\vec{s}_2}{3}\right) V^{(3)}(r) + \frac{\vec{s}_1\,\vec{s}_2}{3m_1m_2} V^{(4)}(r)$$

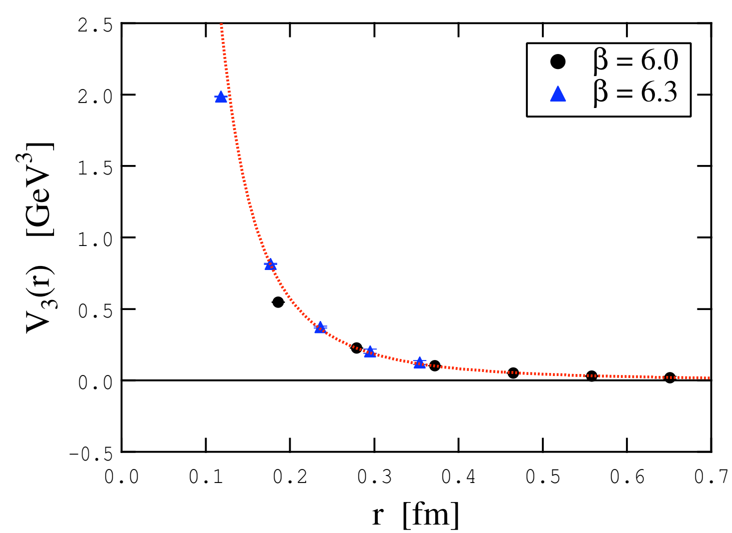
Fine and hyper-fine splitting

Multi-level algorithm allows lattice determination of potentials with unprecedented precision

Y. Koma, M. Koma and H. Wittig [hep-lat/0607009]

Quenched





Recent LQCD results

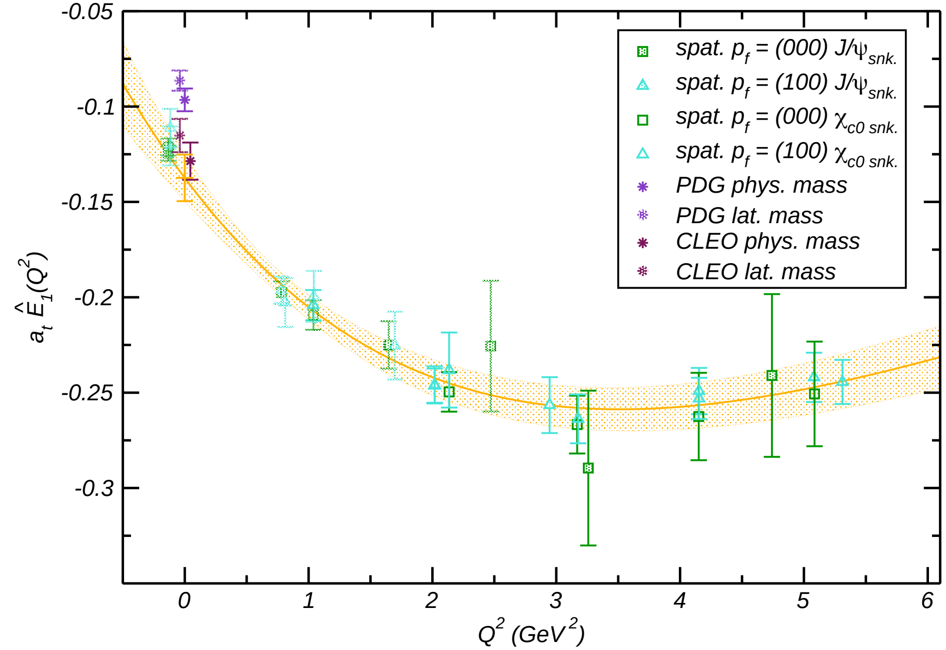
Dudek, Edwards, Richards
hep-lat/0601137
[PR D73:074507 (2006)]

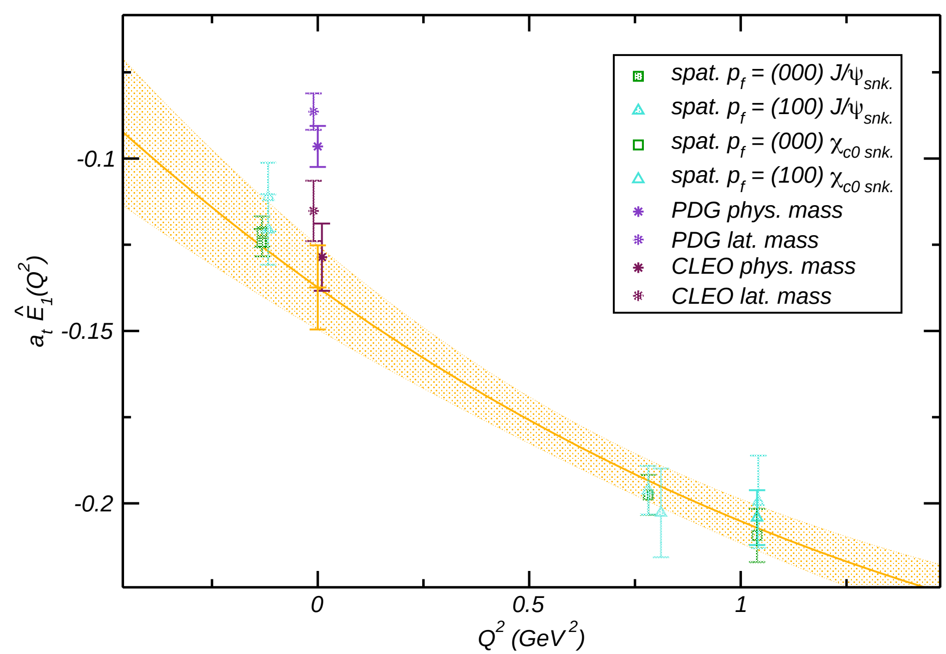
E1	$\chi_{c0} \to J/\psi\gamma$	$\chi_{c1} \to J/\psi\gamma$	$h_c \to \eta_c\gamma$
β/MeV	542(35)	555(113)	689(133)
ρ/MeV	1080(130)	1650(590)	∞
$\Gamma^{\text{lat.mass}}_{\text{phys.mass}}$/keV	288(60) 232(41)	600(178) 487(122)	663(132) 601(55)
$\Gamma^{\text{PDG}}_{\text{CLEO}}$/keV	115(14) 204(31)	303(44) 364(31)	-

M1	$J/\psi \to \eta_c\gamma$	**M2**	$\chi_{c1} \to J/\psi\gamma$
β/MeV	540(10)	β/MeV	617(142)
$\Gamma^{\text{lat.mass}}_{\text{phys.mass}}$/keV	1.61(7) 2.57(11)	$\frac{M2}{E1}$	$-0.199(121)$
$\Gamma^{\text{PDG}}_{\phi\phi}$/keV	1.14(33) 2.9(1.5)	expt.	$-0.002(^{+8}_{-17})$

Promising but still work to do:
quenched
ground states
extrapolations
  $Q^2 \to 0$
  $a \to 0$

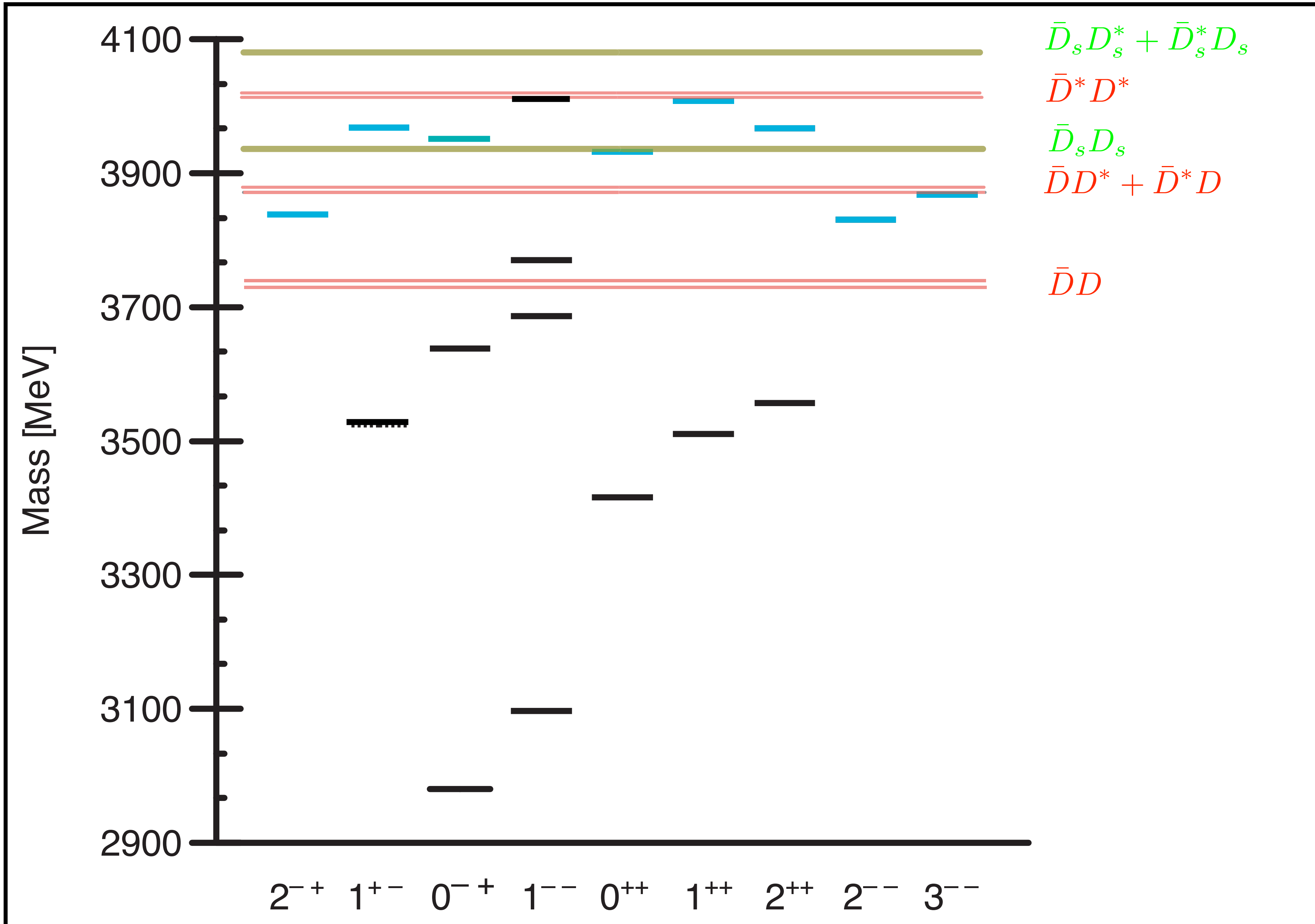
$\chi_{c0} \to J/\psi\gamma$





Above Threshold

Charmonium Spectrum



Nearby Thresholds

TABLE I: Thresholds for decay into open charm and nearby hidden-charm thresholds.

Channel	Threshold Energy (MeV)
$D^0\bar{D}^0$	3729.4
D^+D^-	3738.8
$D^0\bar{D}^{*0}$ or $D^{*0}\bar{D}^0$	3871.5
$\rho^0 J/\psi$	3872.7
$D^\pm D^{*\mp}$	3879.5
$\omega^0 J/\psi$	3879.6
$D_s^+D_s^-$	3936.2
$D^{*0}\bar{D}^{*0}$	4013.6
$D^{*+}D^{*-}$	4020.2
$\eta' J/\psi$	4054.7
$f^0 J/\psi$	$\approx$ 4077
$D_s^+\bar{D}_s^{*-}$ or $D_s^{*+}\bar{D}_s^-$	4080.0
$a^0 J/\psi$	4081.6
$\varphi^0 J/\psi$	4116.4
$D_s^{*+}D_s^{*-}$	4223.8

Hard to extract states in the threshold region in LQCD

Excited states:

$$C(t) \equiv \langle 0|\Phi(t)\Phi^\dagger(0)|0\rangle = \sum_n \langle 0|e^{Ht}\Phi(0)e^{-Ht}|n\rangle\langle n|\Phi^\dagger(0)|0\rangle$$
$$= \sum |\langle 0|\Phi(0)|n\rangle|^2 e^{-(E_n-E_0)t} = \sum A_n e^{-(E_n-E_0)t},$$

To extract N states in same channel - use an NxN two point correlation function obtained from N independent operators

$$C_{\alpha\beta}(t) = \langle 0|\Phi_\alpha(t)\Phi^\dagger_\beta(0)|0\rangle$$

Find principal eigenvectors of

$$C(t_0)^{-1/2}C(t)C(t_0)^{-1/2},$$

Strong decay channels -- resonances:

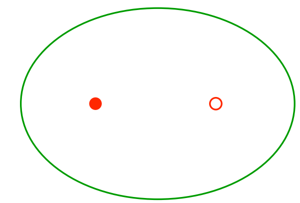
At finite volume (V) only discrete momentum values -
Multimeson states have a discrete spectrum -
Use V dependence to disentangle resonances from multibody states.

QCD Dynamics Near Threshold

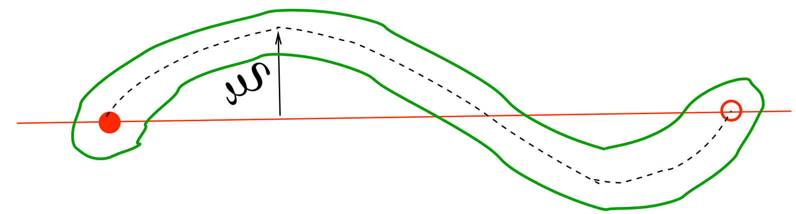
- QCD dynamics is much richer than present phenomological models - Lattice QCD
- Gluon/String dynamics
- Light quark loops and strong decays

Heavy Quark Limit - Static Energy

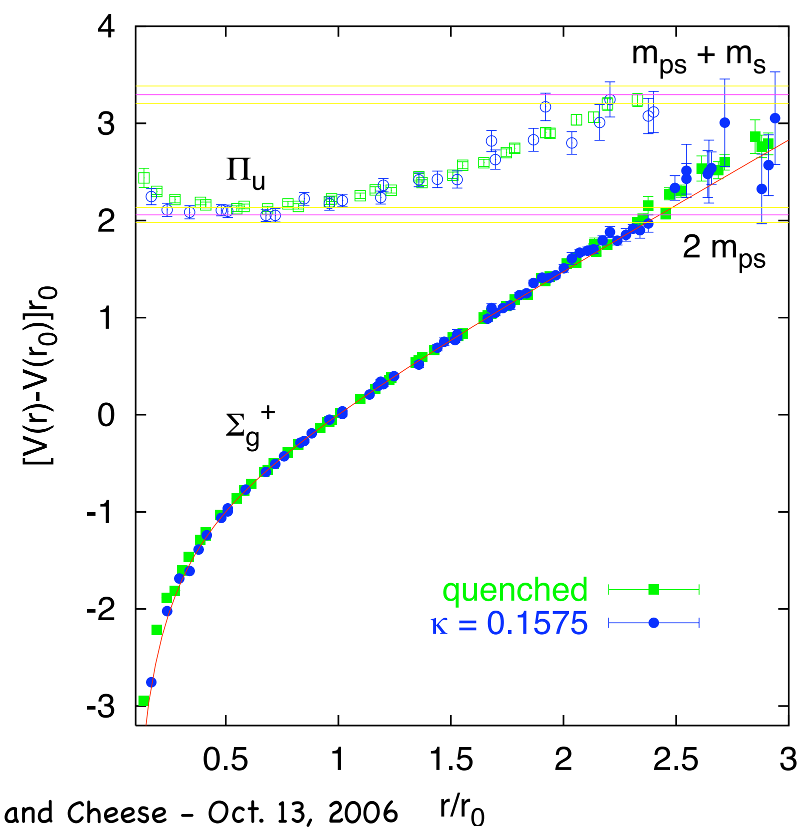
Short distance: Perturbative QCD
singlet: -4/3 α_s /r
octet : 2/3 α_s /r gluelumps



Large distance: String
σ r String behaviour



Hybrids are not narrow
even in heavy quark limit



Operators for excited gluon states

TABLE I: Operators to create excited gluon states for small $q\bar{q}$ separation R are listed. $\mathbf{E}$ and $\mathbf{B}$ denote the electric and magnetic operators, respectively. The covariant derivative $\mathbf{D}$ is defined in the adjoint representation [10].

gluon state	J	operator
$\Sigma_g^{+\prime}$	1	$\mathbf{R}\cdot\mathbf{E}$, $\quad \mathbf{R}\cdot(\mathbf{D}\times\mathbf{B})$
Π_g	1	$\mathbf{R}\times\mathbf{E}$, $\quad \mathbf{R}\times(\mathbf{D}\times\mathbf{B})$
Σ_u^-	1	$\mathbf{R}\cdot\mathbf{B}$, $\quad \mathbf{R}\cdot(\mathbf{D}\times\mathbf{E})$
Π_u	1	$\mathbf{R}\times\mathbf{B}$, $\quad \mathbf{R}\times(\mathbf{D}\times\mathbf{E})$
Σ_g^-	2	$(\mathbf{R}\cdot\mathbf{D})(\mathbf{R}\cdot\mathbf{B})$
Π_g'	2	$\mathbf{R}\times((\mathbf{R}\cdot\mathbf{D})\mathbf{B}+\mathbf{D}(\mathbf{R}\cdot\mathbf{B}))$
Δ_g	2	$(\mathbf{R}\times\mathbf{D})^i(\mathbf{R}\times\mathbf{B})^j+(\mathbf{R}\times\mathbf{D})^j(\mathbf{R}\times\mathbf{B})^i$
Σ_u^+	2	$(\mathbf{R}\cdot\mathbf{D})(\mathbf{R}\cdot\mathbf{E})$
Π_u'	2	$\mathbf{R}\times((\mathbf{R}\cdot\mathbf{D})\mathbf{E}+\mathbf{D}(\mathbf{R}\cdot\mathbf{E}))$
Δ_u	2	$(\mathbf{R}\times\mathbf{D})^i(\mathbf{R}\times\mathbf{E})^j+(\mathbf{R}\times\mathbf{D})^j(\mathbf{R}\times\mathbf{E})^i$

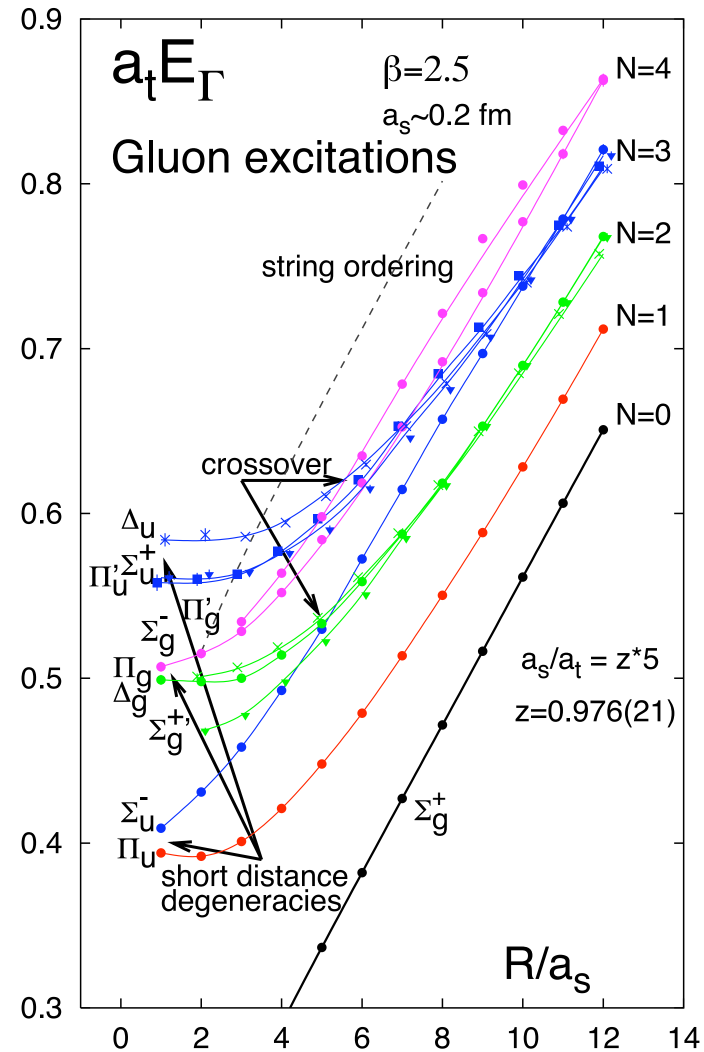


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

Juge, Kuti, Morningstar

PRL 82:4400 (1999); 90:161601 (2003)

Hybrid Potentials

Solve the Schoedinger Equation for each potential

$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2}+\left\{\frac{\langle \boldsymbol{L}^2_{Q\bar{Q}}\rangle}{2\mu r^2}+V_{Q\bar{Q}}(r)\right\}u(r)=E\,u(r),$$

where

$$\boldsymbol{J}=\boldsymbol{L}+\boldsymbol{S},\quad \boldsymbol{S}=\boldsymbol{s}_Q+\boldsymbol{s}_{\bar{Q}},\quad \boldsymbol{L}=\boldsymbol{L}_{Q\bar{Q}}+\boldsymbol{J}_g$$

$$\langle \boldsymbol{L}^2_{Q\bar{Q}}\rangle = L(L+1)-2\Lambda^2+\langle \boldsymbol{J}^2_g\rangle$$

eigenstates

$$|LSJM;\lambda\eta\rangle+\varepsilon|LSJM;-\lambda\eta\rangle$$

where $\varepsilon = \pm 1$, $\Lambda = |\lambda|$

$$P=\varepsilon(-1)^{L+\Lambda+1},\qquad C=\eta\varepsilon(-1)^{L+S+\Lambda}$$

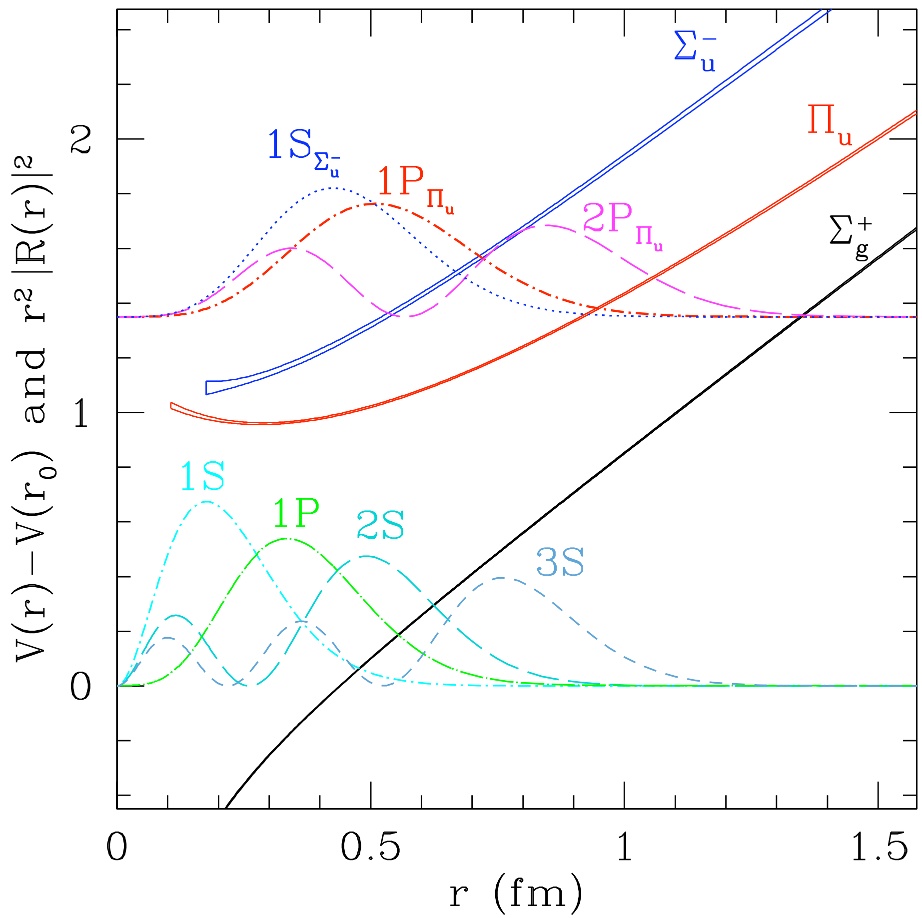
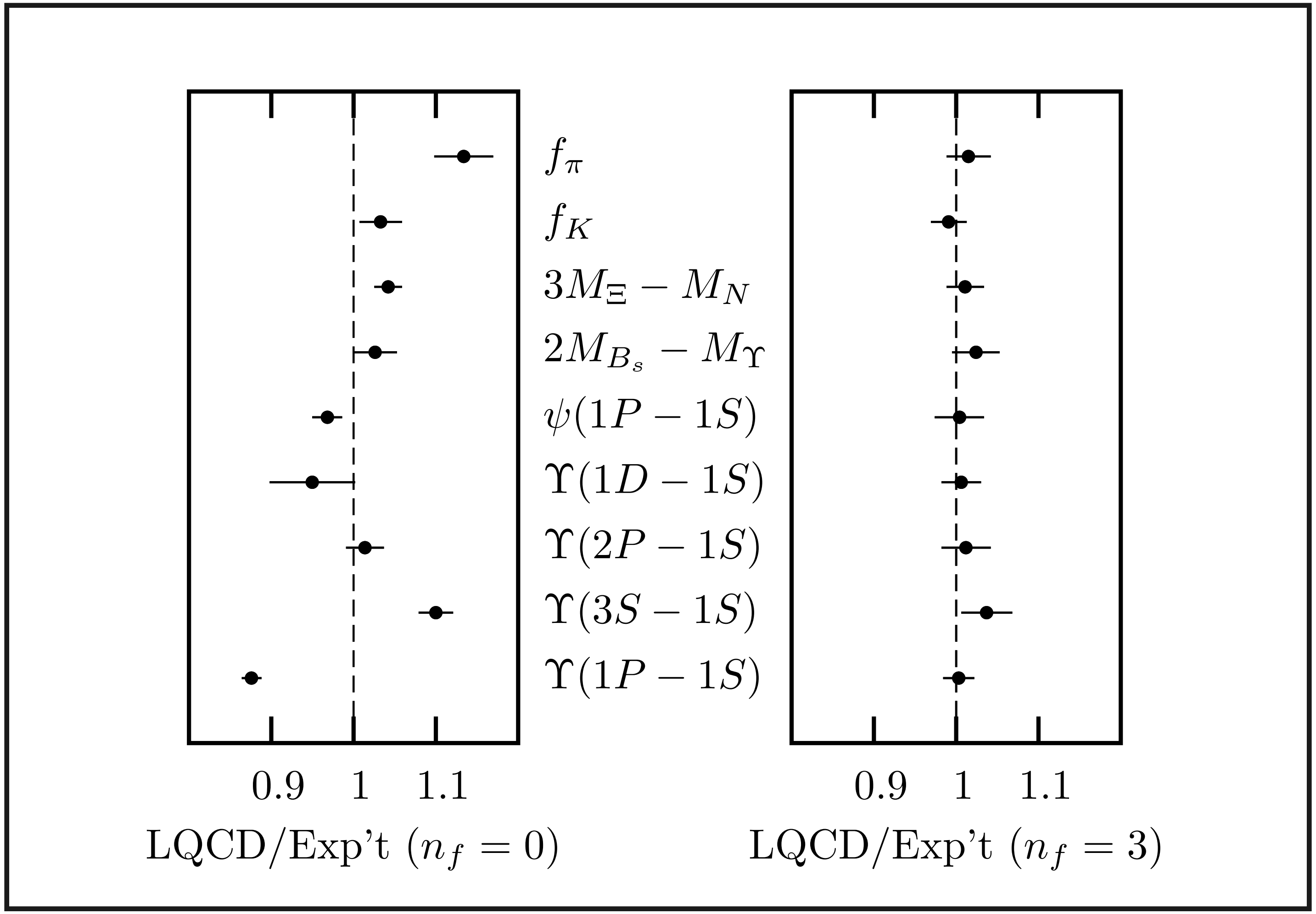


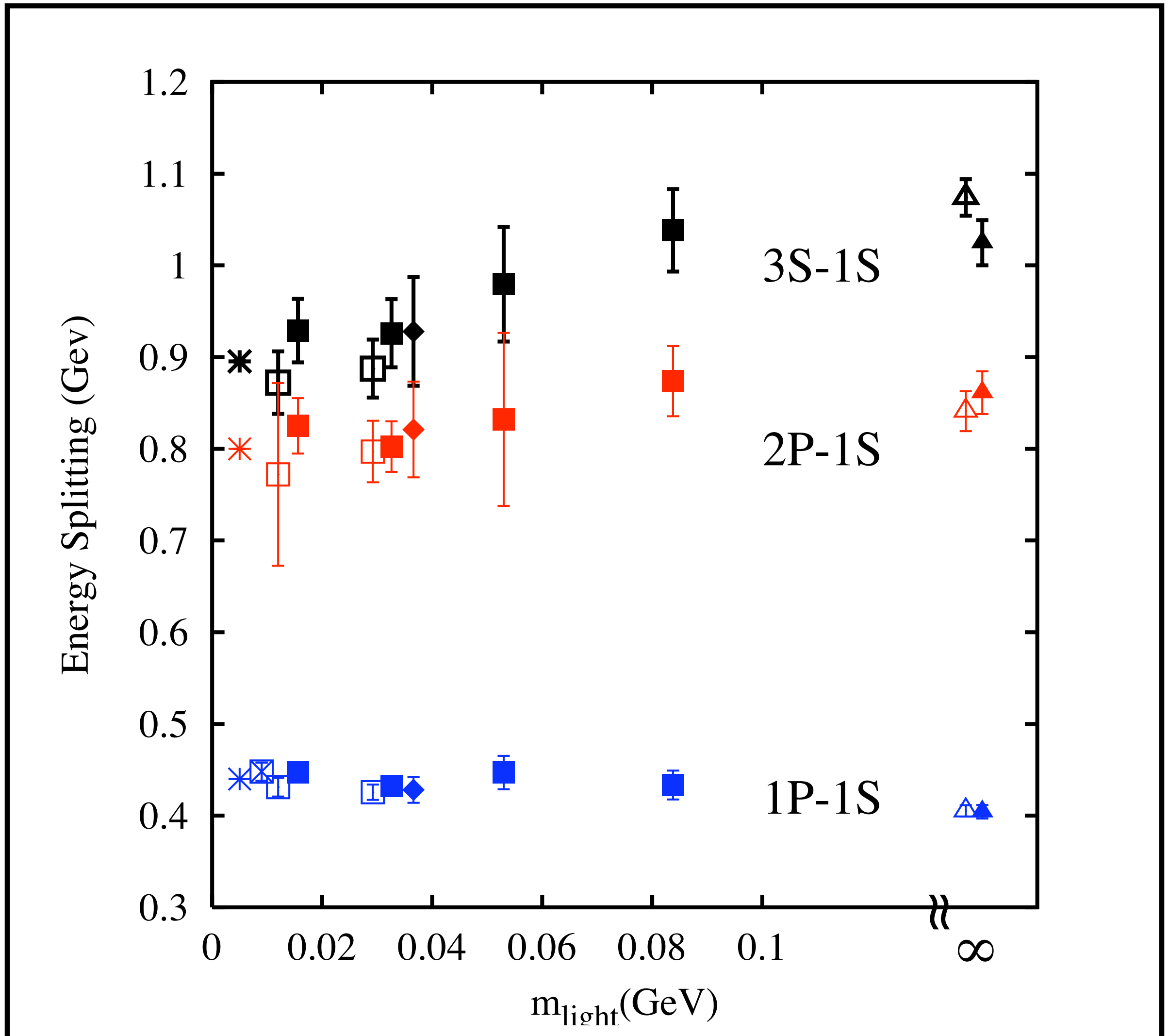
Figure 2. Wavefunctions and potentials for the various hybrid/meson states.

Lattice QCD - light quark loops



C. T. H. Davies et al. [HPQCD, Fermilab Lattice, MILC, and UKQCD Collaborations], Phys. Rev. Lett. 92, 022001 (2004) [arXiv:hep-lat/0304004].

Dependence on light quark mass



Including Light Quark Effects

$$[\mathcal{H}_0 + \mathcal{H}_2 + \mathcal{H}_I]\psi = \omega\psi$$

$\mathcal{H}_0$ $Q\bar{Q}$ NRQCD (without couplings light quarks)

$\mathcal{H}_I$ $Q\bar{Q} \Longrightarrow Q\bar{q}+q\bar{Q}$ light quark pair creation

Cornell model (CCCM) $\mathcal{H}_I = \frac{3}{8}\sum_a \int :\rho_a(\mathbf{r})V(\mathbf{r}-\mathbf{r}')\rho_a(\mathbf{r}'):d^3r\,d^3r'$

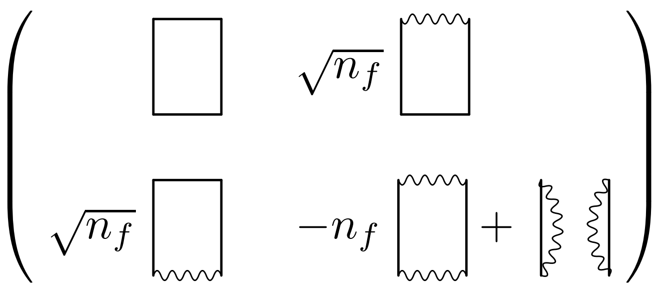
Vacuum Pair Creation model (QPC) $\mathcal{H}_I = \gamma \int \bar{\psi}\psi(\mathbf{r})d^3r$

$\mathcal{H}_2$ $Q\bar{q}+q\bar{Q}$ meson pair interactions

Lattice effort to extract couplings

$$C(t) = \begin{pmatrix} C_{QQ}(t) & C_{QB}(t) \\ C_{BQ}(t) & C_{BB}(t) \end{pmatrix}$$

$= e^{-2m_Q t}$



, (1)

transition amplitude

$$g = \left.\frac{dC_{QB}(t)}{dt}\right|_{t=0} \frac{1}{\sqrt{C_{BB}(0)C_{QQ}(0)}}.$$

difficult to extract accurately

G.S. Bali, H. Neff, T. Düssel, T. Lippert and K. Schilling [SESAM Collaboration], *Phys. Rev. D* **71**, 114513 (2005) [arXiv:hep-lat/0505012].

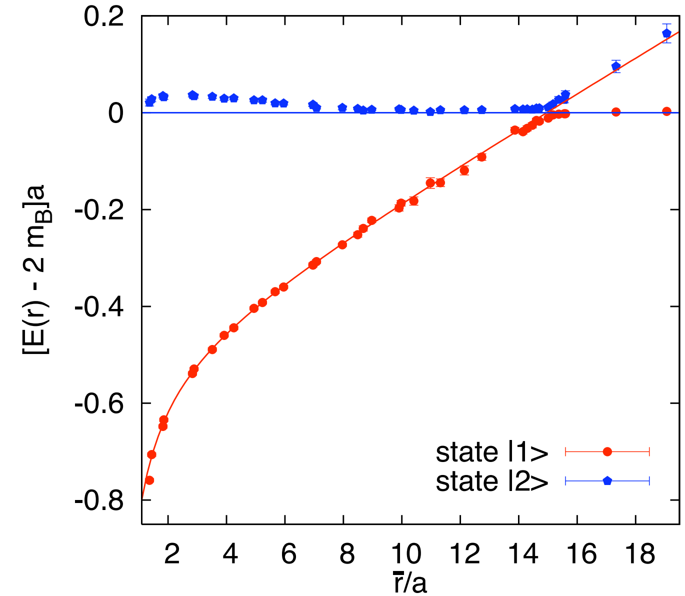


FIG. 13: The two energy levels, as a function of $\overline{r}$, normalized with respect to $2m_B$ (horizontal line). The curve corresponds to the three parameter fit to $E_1(\overline{r})$, Eqs. (80)–(82), for $0.2\,\mathrm{fm} \le \overline{r} \le 0.9\,\mathrm{fm} < r_c$.

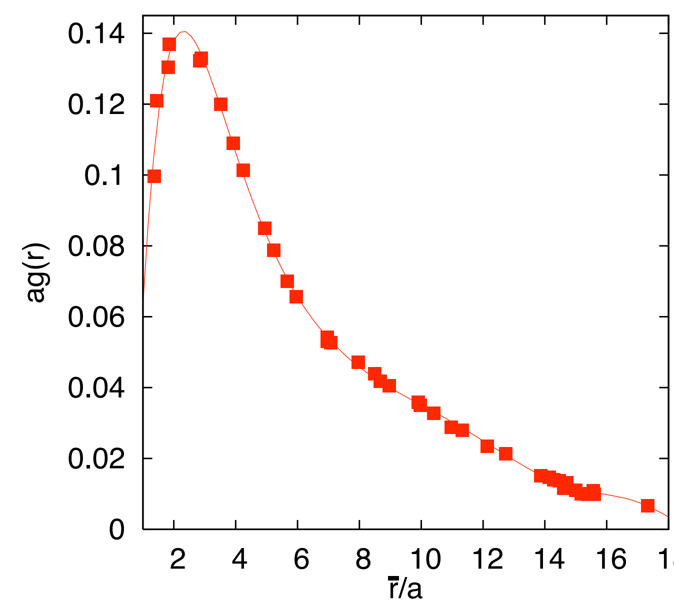


FIG. 18: The transition rate g between $|B\rangle$ and $|Q\rangle$ states, as a function of $\overline{r}$.

Coupling to open-charm channels

Phenomenological approach:

$$\boxed{\begin{aligned}&\mathcal{H}_I = \tfrac{3}{8}\textstyle\sum_a \int : \rho_a(\mathbf{r}) V(\mathbf{r}-\mathbf{r}')\rho_a(\mathbf{r}') : d^3r\, d^3r' \\ &\rho^a = \bar{c}\gamma^0 t^a c + \bar{q}\gamma^0 t^a q\end{aligned}}$$

CCCM

Calculate pair-creation amplitudes,

Evaluate $\boxed{<^3 D_2|\mathcal{H}_I|D\bar{D}^\star >}$, etc.

ELQ 2004

Solve coupled-state system

$$\boxed{\psi = \underset{\bar{c}c}{\psi_0} + \underset{\bar{D}D}{\psi_2}}$$

solve $\boxed{\left[\mathcal{H}_0 + \mathcal{H}_I^\dagger \frac{1}{\omega - \mathcal{H}_2 + i\epsilon}\mathcal{H}_I\right]\psi_0 = \omega\psi_0}$

for ω and ψ_0

Statistical Factors in Strong Decays

TABLE II: Statistical recoupling coefficients C, defined by Eq. D19 of Ref. [10], that enter the calculation of charmonium decays to pairs of charmed mesons. Paired entries correspond to $\ell = L - 1$ and $\ell = L + 1$.

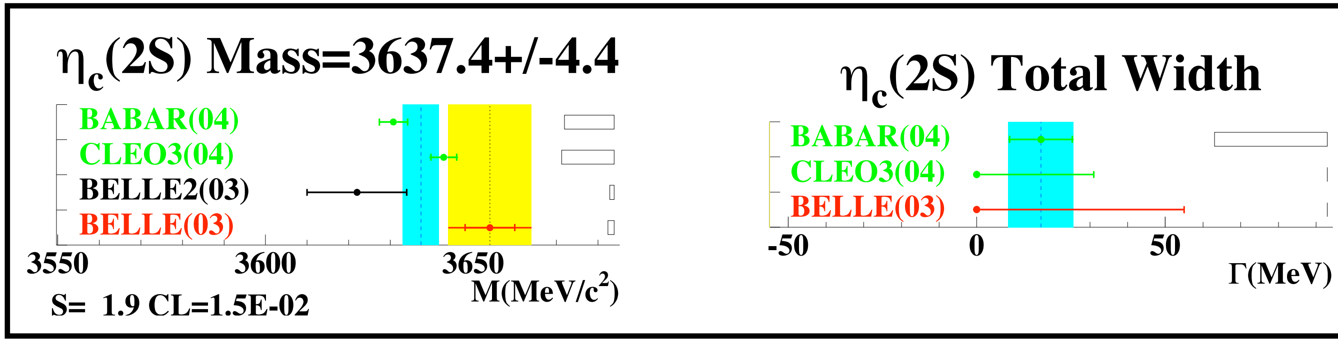
State	$D\bar{D}$	$D\bar{D}^*$	$D^*\bar{D}^*$
⇒ $^1S_0$	$- : 0$	$- : 2$	$- : 2$
$^3S_1$	$- : \frac{1}{3}$	$- : \frac{4}{3}$	$- : \frac{7}{3}$
$^3P_0$	$1 : 0$	$0 : 0$	$\frac{1}{3} : \frac{8}{3}$
$^3P_1$	$0 : 0$	$\frac{4}{3} : \frac{2}{3}$	$0 : 2$
$^1P_1$	$0 : 0$	$\frac{2}{3} : \frac{4}{3}$	$\frac{2}{3} : \frac{4}{3}$
⇒ $^3P_2$	$0 : \frac{2}{5}$	$0 : \frac{6}{5}$	$\frac{4}{3} : \frac{16}{15}$
$^3D_1$	$\frac{2}{3} : 0$	$\frac{2}{3} : 0$	$\frac{4}{15} : \frac{12}{5}$
$^3D_2$	$0 : 0$	$\frac{6}{5} : \frac{4}{5}$	$\frac{2}{5} : \frac{8}{5}$
$^1D_2$	$0 : 0$	$\frac{4}{5} : \frac{6}{5}$	$\frac{4}{5} : \frac{6}{5}$
⇒ $^3D_3$	$0 : \frac{3}{7}$	$0 : \frac{8}{7}$	$\frac{8}{5} : \frac{29}{35}$
$^3F_2$	$\frac{3}{5} : 0$	$\frac{4}{5} : 0$	$\frac{11}{35} : \frac{16}{7}$
$^3F_3$	$0 : 0$	$\frac{8}{7} : \frac{6}{7}$	$\frac{4}{7} : \frac{10}{7}$
$^1F_3$	$0 : 0$	$\frac{6}{7} : \frac{8}{7}$	$\frac{6}{7} : \frac{8}{7}$
$^3F_4$	$0 : \frac{4}{9}$	$0 : \frac{10}{9}$	$\frac{12}{7} : \frac{46}{63}$
$^3G_3$	$\frac{4}{7} : 0$	$\frac{6}{7} : 0$	$\frac{22}{63} : \frac{20}{9}$
$^3G_4$	$0 : 0$	$\frac{10}{9} : \frac{8}{9}$	$\frac{2}{3} : \frac{4}{3}$
$^1G_4$	$0 : 0$	$\frac{8}{9} : \frac{10}{9}$	$\frac{8}{9} : \frac{10}{9}$
$^3G_5$	$0 : \frac{5}{11}$	$0 : \frac{12}{11}$	$\frac{16}{9} : \frac{67}{99}$

Effects on the spectrum

Coupling to virtual channels induces spin-dependent forces in charmonium near threshold, because M(D*) > M(D)

	State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
	1^1S_0	$2\,979.9^a$	$3\,067.6^b$	-90.5^e	$+2.8$
	1^3S_1	$3\,096.9^a$		$+30.2^e$	-0.9
	1^3P_0	$3\,415.3^a$	$3\,525.3^c$	-114.9^e	$+5.9$
	1^3P_1	$3\,510.5^a$		-11.6^e	-2.0
⇒	1^1P_1	$3\,524.4^f$		$+0.6^e$	$+0.5$
	1^3P_2	$3\,556.2^a$		$+31.9^e$	-0.3
⇒	2^1S_0	$3\,638^a$	$3\,674^b$	-50.1^e	$+15.7$
	2^3S_1	$3\,686.0^a$		$+16.7^e$	-5.2
⇒	1^3D_1	$3\,769.9^a$	$(3\,815)^d$	-40	-39.9
	1^3D_2	$3\,830.6$		0	-2.7
	1^1D_2	$3\,838.0$		0	$+4.2$
⇒	1^3D_3	$3\,868.3$		$+20$	$+19.0$
	2^3P_0	$3\,881.4$	$(3\,922)^d$	-90	$+27.9$
	2^3P_1	$3\,920.5$		-8	$+6.7$
	2^1P_1	$3\,919.0$		0	-5.4
	2^3P_2	$3\,931^g$		$+25$	-9.6
	3^1S_0	$3\,943^h$	$(4\,015)^i$	-66^e	-3.1
	3^3S_1	$4\,040^a$		$+22^e$	$+1.0$

Mass shifts:



$M(\eta_c') = 3637.7 \pm 4.4$

Hyperfine splitting:

$$M(\psi') - M(\eta_c') = 32\pi\alpha_s|\Psi(0)|^2/9m_c^2$$

Normalize to

$$M(J/\psi) - M(\eta_c) = 117\ \mathrm{MeV}$$

$$M(\psi') - M(\eta_c') = 67\ \mathrm{MeV}$$

Observed

$$(48.3 \pm 4.4)\ \mathrm{MeV}$$

Shift

20.9MeV ⇒ Agrees

Modified State Properties

- Mixing

$$\Psi(1^3S_1) = 0.983\,|1^3S_1\rangle - 0.050\,|2^3S_1\rangle - 0.009\,|3^3S_1\rangle + \ldots;\ 96.8\%(c\bar{c})$$

$$\Psi(1^3P_1) = 0.914\,|1^3P_1\rangle - 0.075\,|2^3P_1\rangle - 0.015\,|3^3P_1\rangle + \ldots;\ 84.1\%(c\bar{c})$$

$$\Psi(1^3D_2) = 0.754\,|1^3D_2\rangle - 0.084\,|2^3D_2\rangle - 0.011\,|3^3D_2\rangle + \ldots;\ 57.6\%(c\bar{c})$$

- Isospin breaking P wave decay - 6%

- Radiative Transitions

$1^3D_1(3770) \to$	$\chi_{c2}\,\gamma(208)$	$\chi_{c1}\,\gamma(251)$	$\chi_{c0}\,\gamma(338)$
model	3.9	59	225
experiment[a]	< 20	78 ± 20	172 ± 30
$1^3D_2(3831) \to$	$\chi_{c2}\,\gamma(266)$	$\chi_{c1}\,\gamma(308)$	
model	45	212	
$1^3D_3(3868) \to$	$\chi_{c2}\,\gamma(303)$		
model	286		

Decays into open charm

ψ″(3770) width agrees
with experiment

$^3D_2$ $^1D_2$

No strong decays below

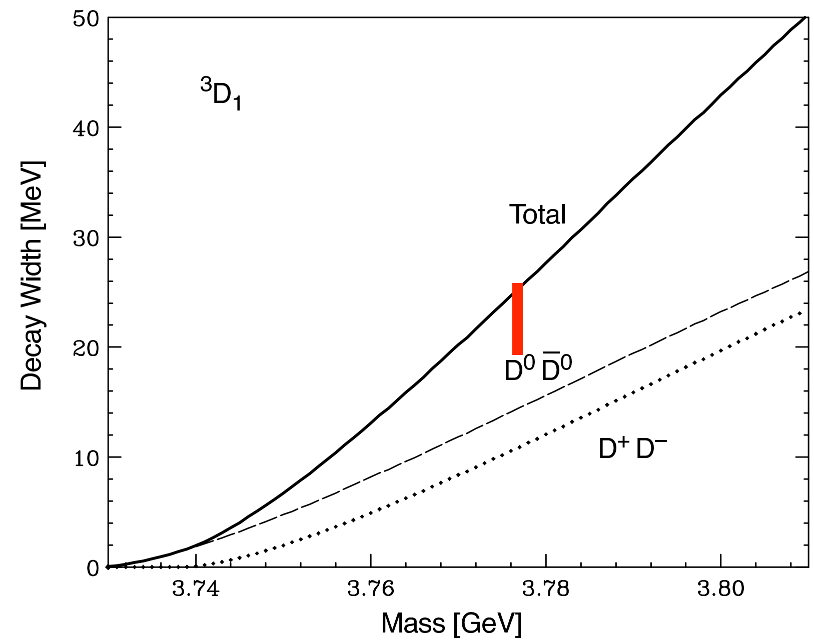
$D\bar{D}^* + \bar{D}D^*$ threshold

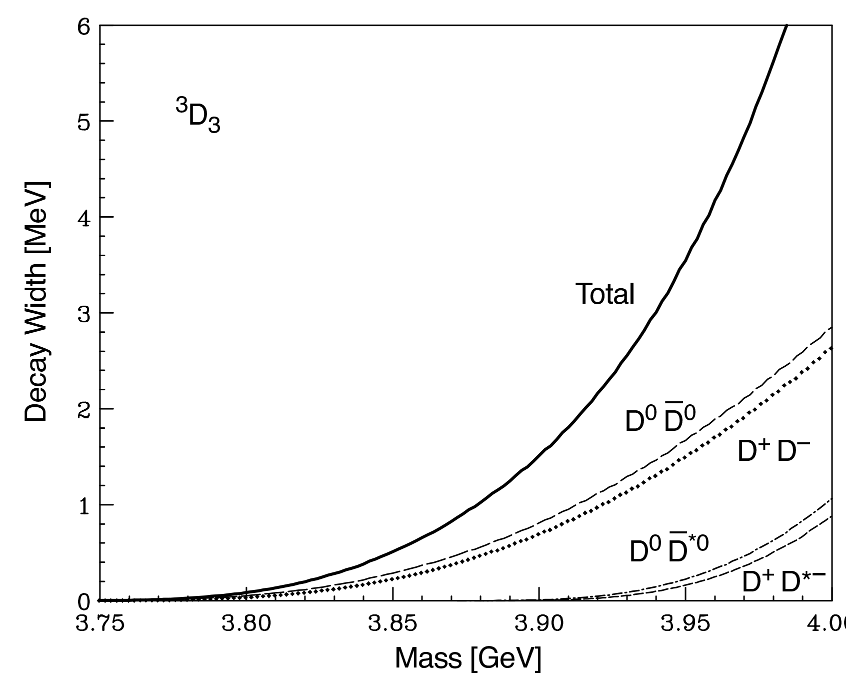
$^3D_3$ decay width small

search in $D\bar{D}$ channel

All remaining 1D states are narrow

How to produce these states?





The X Y Z States

X(3872) — Belle, August 2003

decays into $J/\psi\ \pi^+\pi^-,\ J/\psi\ \pi^+\pi^-\pi^0,\ J/\psi\ \gamma,\ D^0\bar{D}^0\ \pi^0$

Y(3940) — Belle, August 2004

decays into $J/\psi\ \omega$

Y(4260) — BaBar, June 2005

decays into $e^+e^-,\ J/\psi\ \pi^+\pi^-,\ J/\psi\ \pi^0\pi^0,\ J/\psi\ K^+K^-$

X(3943) — Belle, July 2005

decays into $D\bar{D}^*$

Z(3930) — Belle, July 2005

decays into $\gamma\gamma,\ D\bar{D}$

Y(4350) — BaBar, June 2006

decays into $e^+e^-,\ \psi'\ \pi^+\pi^-$

Basic Questions in Charm Threshold Region:

- Is it a new state?
- Charmonium or not?

Including light quark and string effects seems to blur the distinction between charmonium and molecules, hybrids, etc.

Not true for narrow states near thresholds.

A molecular or hybrid state exists only if an addition narrow state is seen in a given channel.

Purely counting states.

Levinson's theorem
Schwinger

- If not what?

Z(3930)

Belle observes the Z(3930) in ΥΥ production

Phys. Rev. Lett. 96, 082003 (2006)

$$J^{PC} = 0^{++} \text{ or } 2^{++}$$

Mass = 3929 ± 5(stat) ± 2(sys) MeV

Width = 29 ± 10(stat) ± 2(sys) MeV

Decay mode $\bar{D}D$

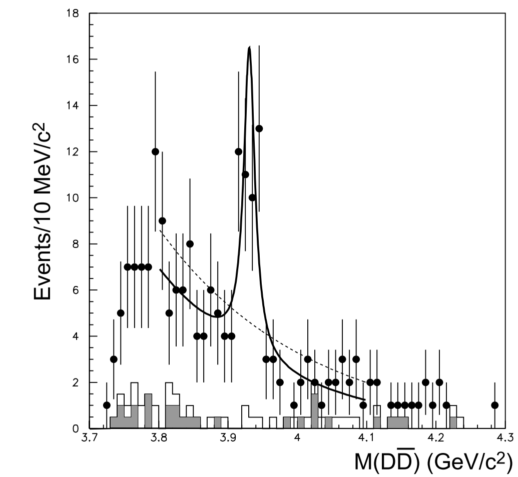
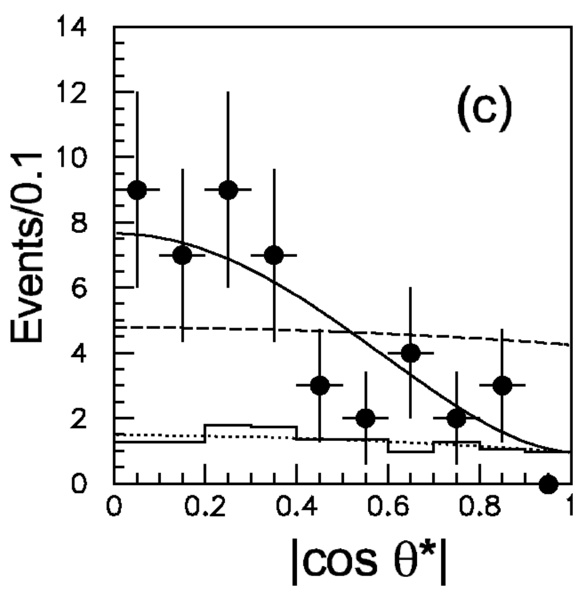


FIG. 3: The sum of the $M(D\bar{D})$ invariant mass distributions for all four processes. The curves show the fits with (solid) and without (dashed) a resonance component. The histograms show the distribution of the events from the D-mass sidebands (see the text).

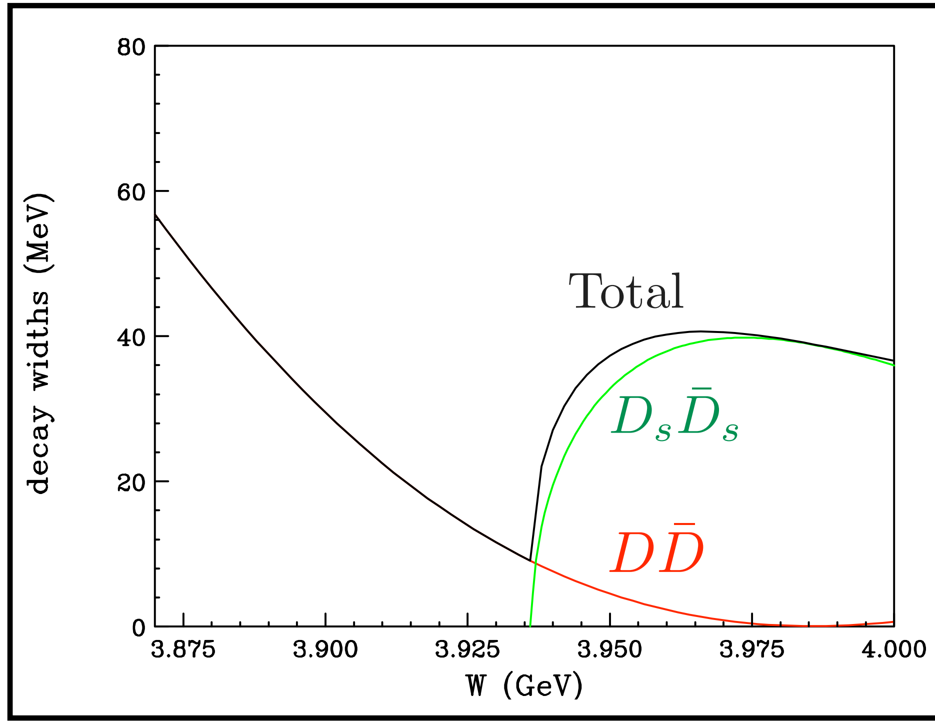


DD angular distribution favors J=2

2P States

$$2\ {}^3P_0$$

Surprisingly narrow width
- but J = 0 disfavored



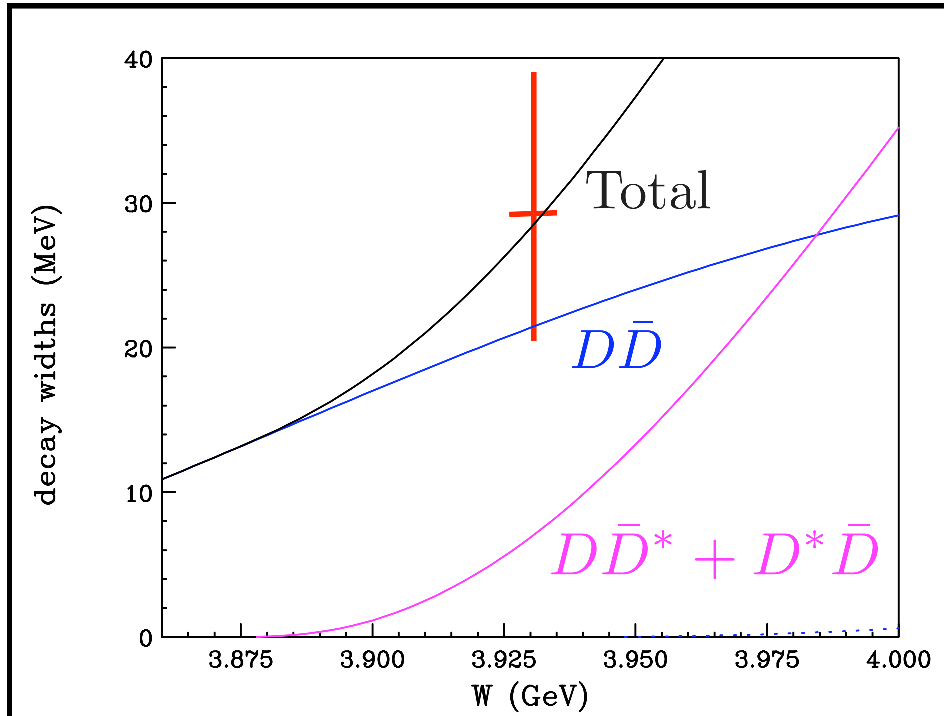
✓ $$2\ {}^3P_2$$

model $\Gamma = 29\ \mathrm{MeV}$

$$\frac{D\bar{D}^* + D^*\bar{D}}{D\bar{D}} = 0.32$$

$$\frac{D^+\bar{D}^-}{D^0\bar{D}^0} = 0.95 \qquad 0.74 \pm 0.43 \pm 0.16$$

exp



Z(3930) likely χ'_{c2}

X(3943)

Belle [hep-ex/0507019]

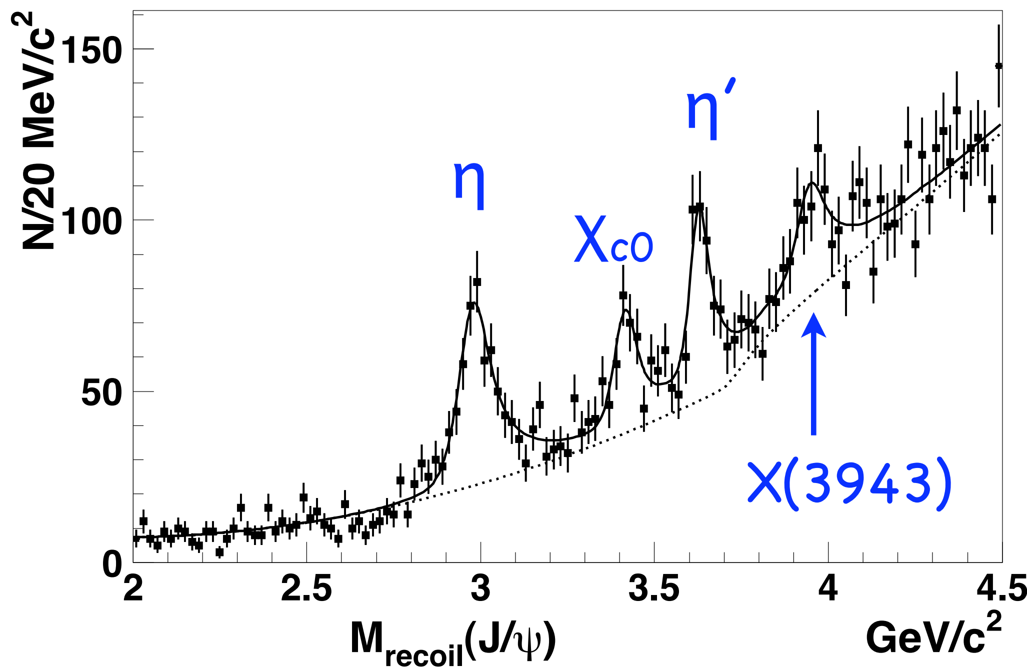
Belle observes the X(3943) in recoil against the J/ψ

Mass = 3936 ± 14 MeV

Width = 39 ± 26 MeV

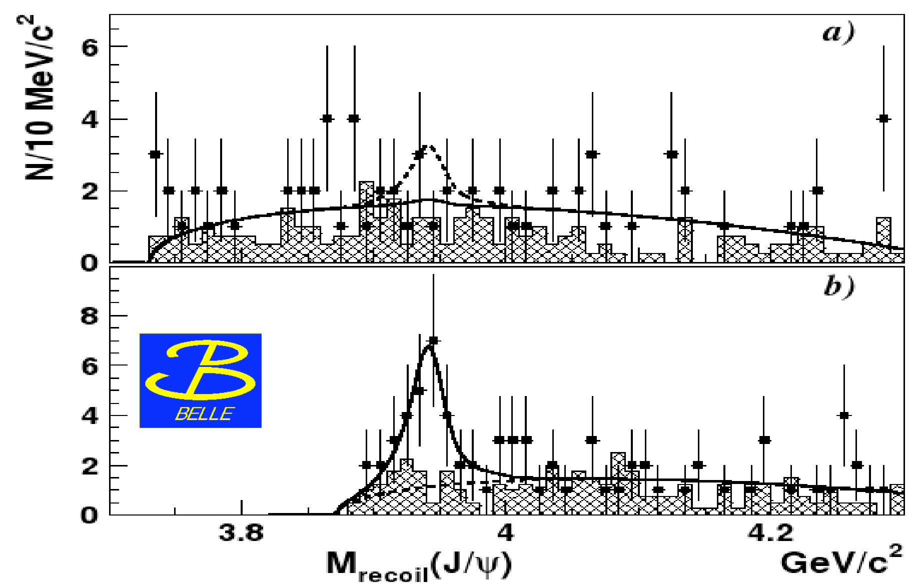
M(ψ(4040) - X(3943)) ≈ 100 MeV

Large



$$\mathrm{BR}(D\bar{D}) < 41\% \text{ @ } 90\% cl$$

$$\mathrm{BR}(D\bar{D}^* + D^*\bar{D}) > 45\% \text{ @ } 90\% cl$$



Not a $^3P_0$ state

Likely the η_c'' state, but

Coupled Channels Results for η_c''

$\Gamma \approx 50$ MeV

3S Spin Splitting
increased

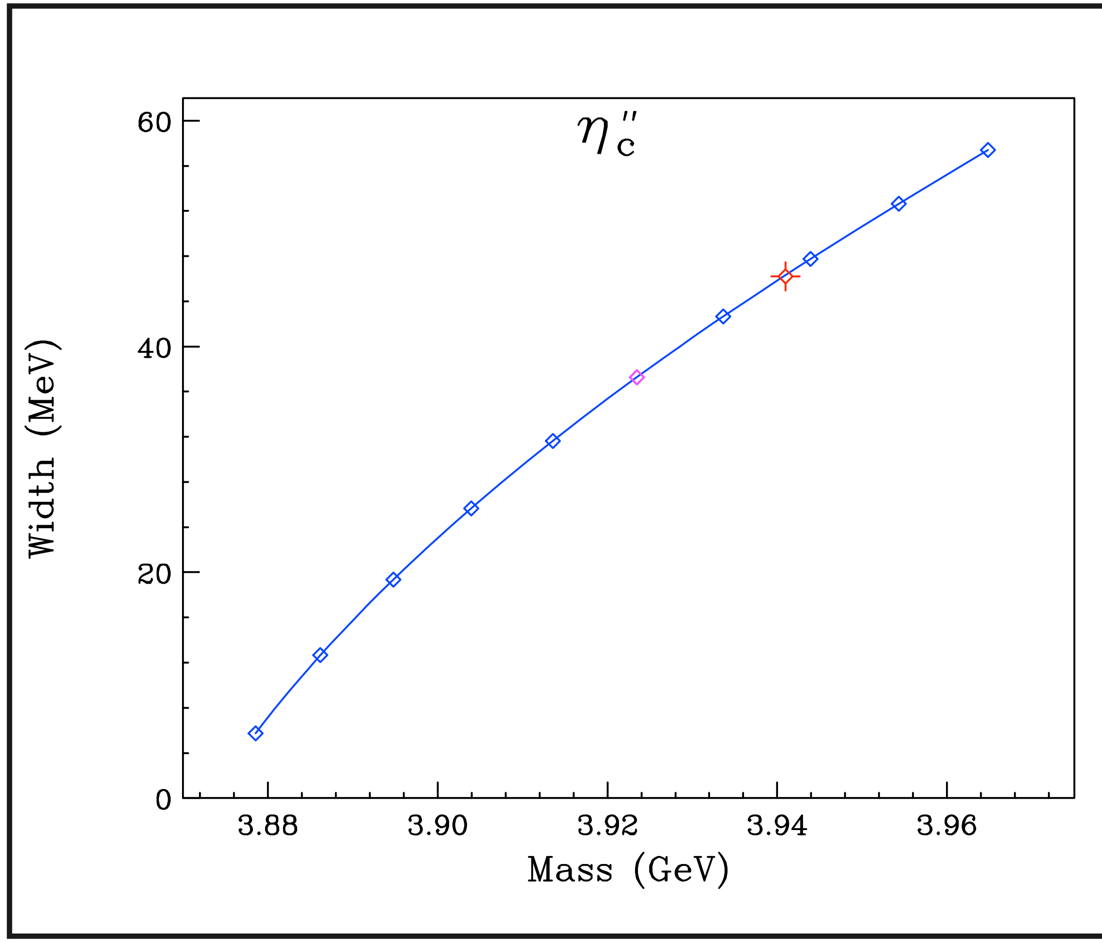
Requires bare splitting:
88 Mev

To check:

Extract 3^3S_1 pole from CCC model of ΔR.

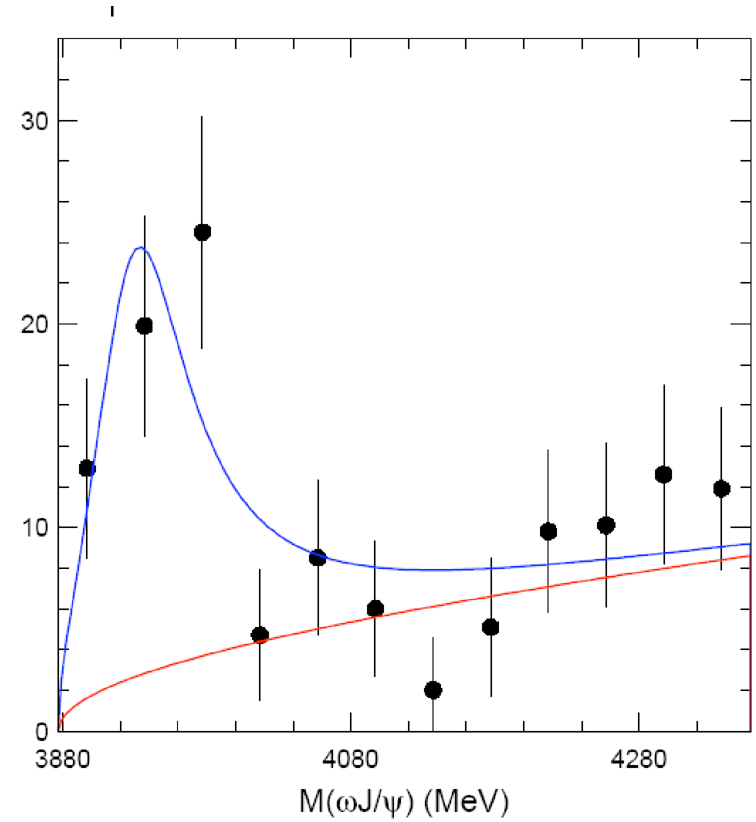
✓ No improvement

Including DDp channels:
Expected to add significant spin splitting



Y(3940)

Belle [PRL94, 182002 (2005)]



Belle observes the Y(3940) in B decays to K ω J/ψ

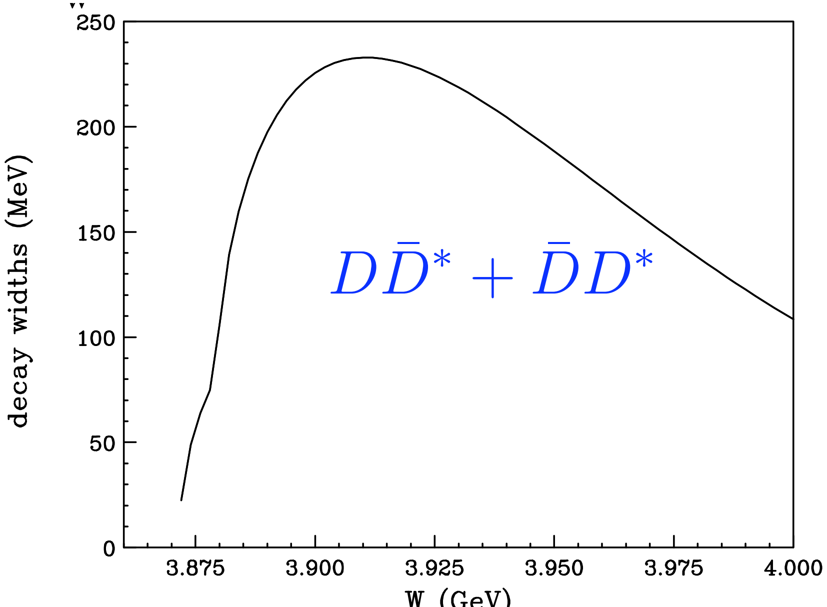
Mass = 3940 ± 11 MeV

Width = 92 ± 24 MeV

Decay mode seen: ω J/ψ

$2\ {}^3P_1$?

Decay width versus mass



Not a good fit - mass, width, modes

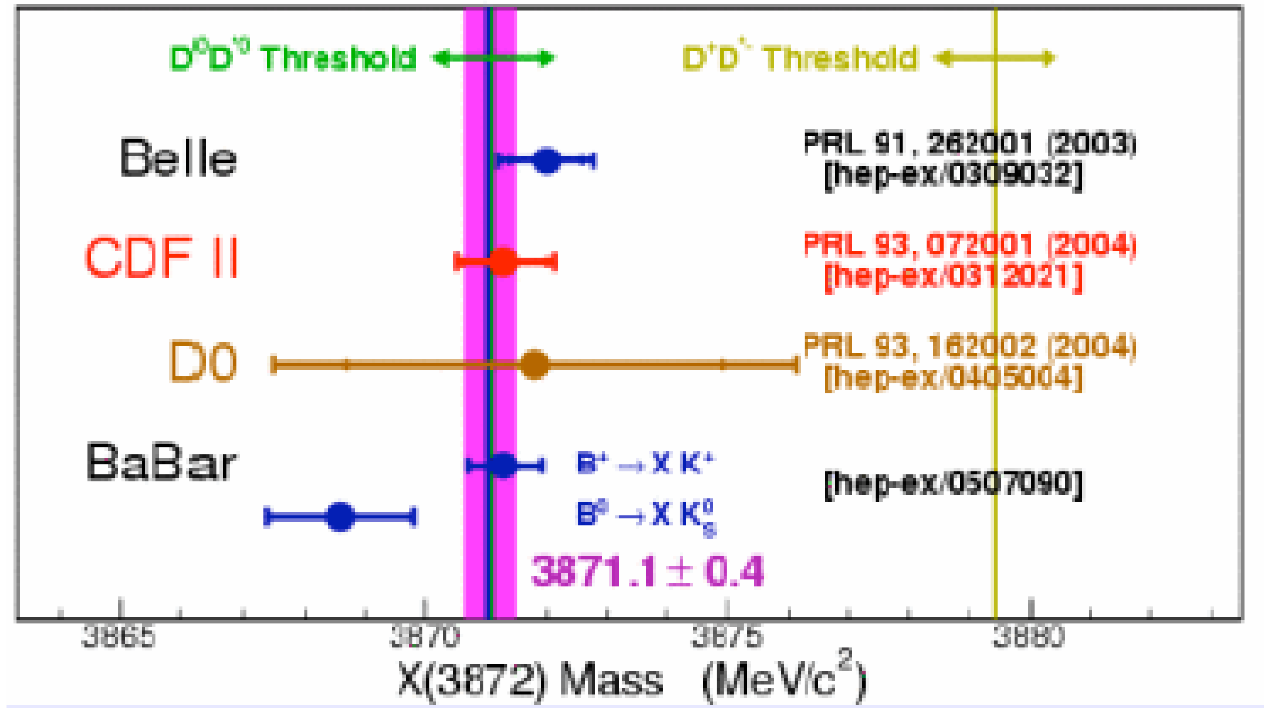
Y(3940) needs confirmation

X(3872)

Production:

Belle and BaBar - Produced in B decays.

CDF and D0 - Significant prompt production.



Mass

3.871.2 ± 0.5 MeV

DD* thresholds:

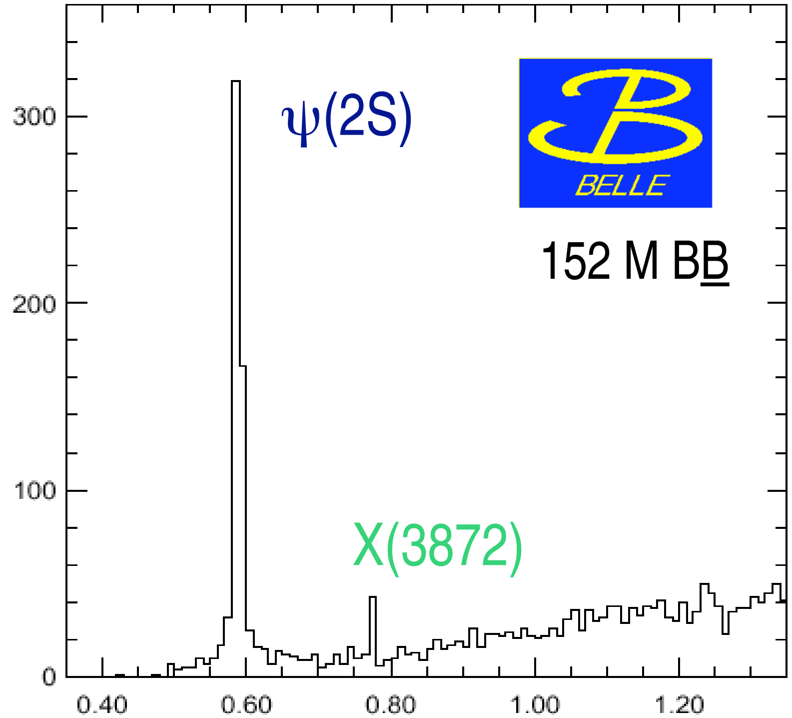
0	3.871.1 ± 0.8 MeV	PDG06
+	3.877.7 ± 0.8 MeV	

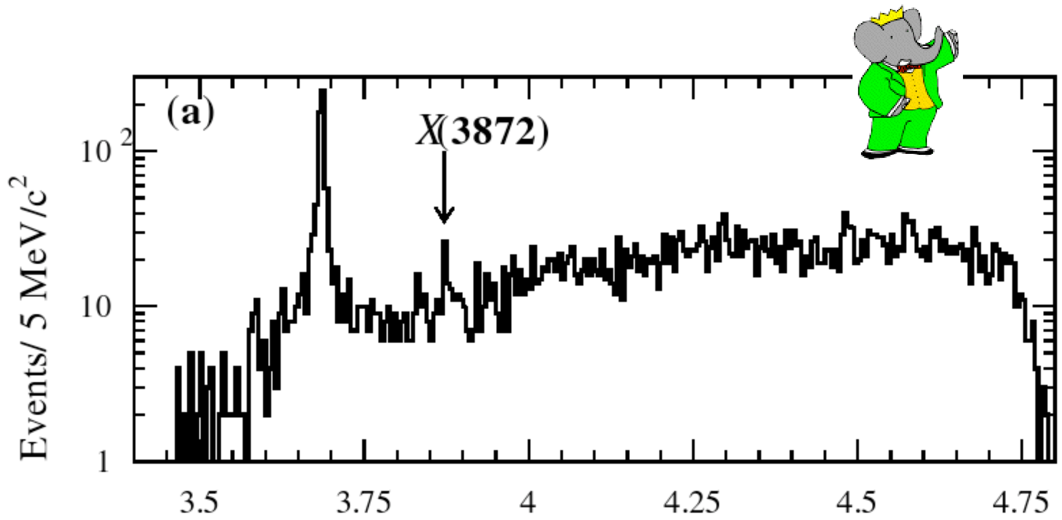
$$M(X) - M(D^0) - M(\bar{D}^{*0}) = -0.4 \pm 0.7 \text{ MeV}$$

CLEO Preliminary
More precise D masses

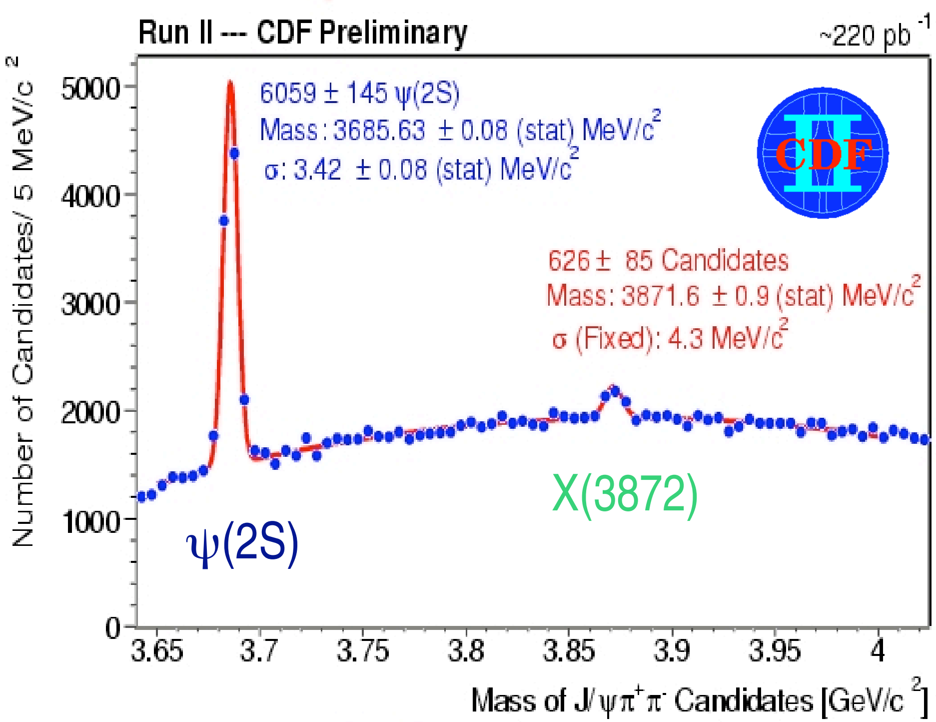
Width < 2.3 MeV @ 90 % c.l. Belle

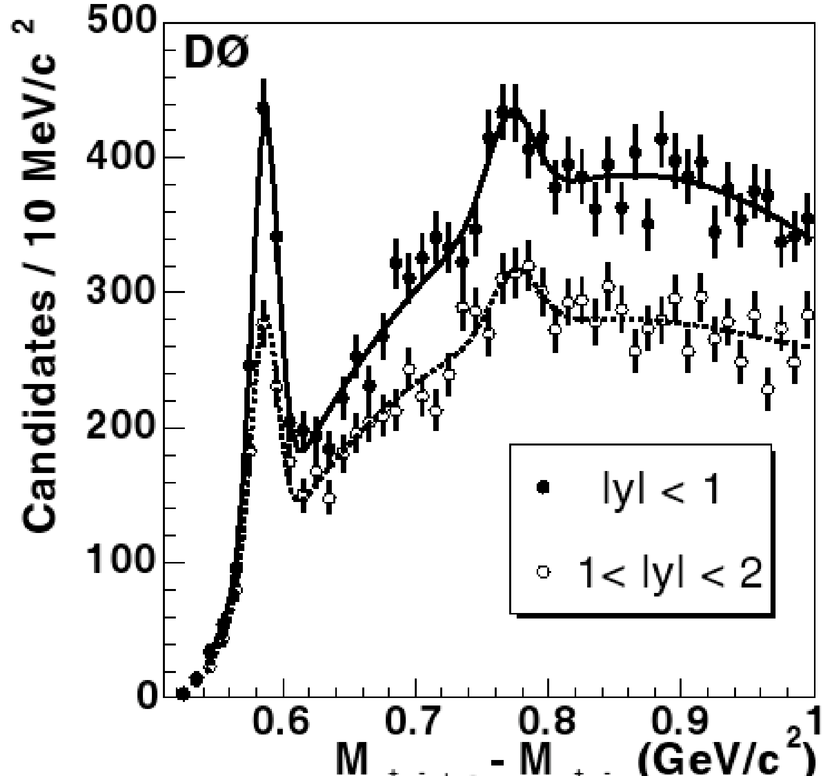
Decays: $\pi^+\pi^- J/\psi$ discovery mode



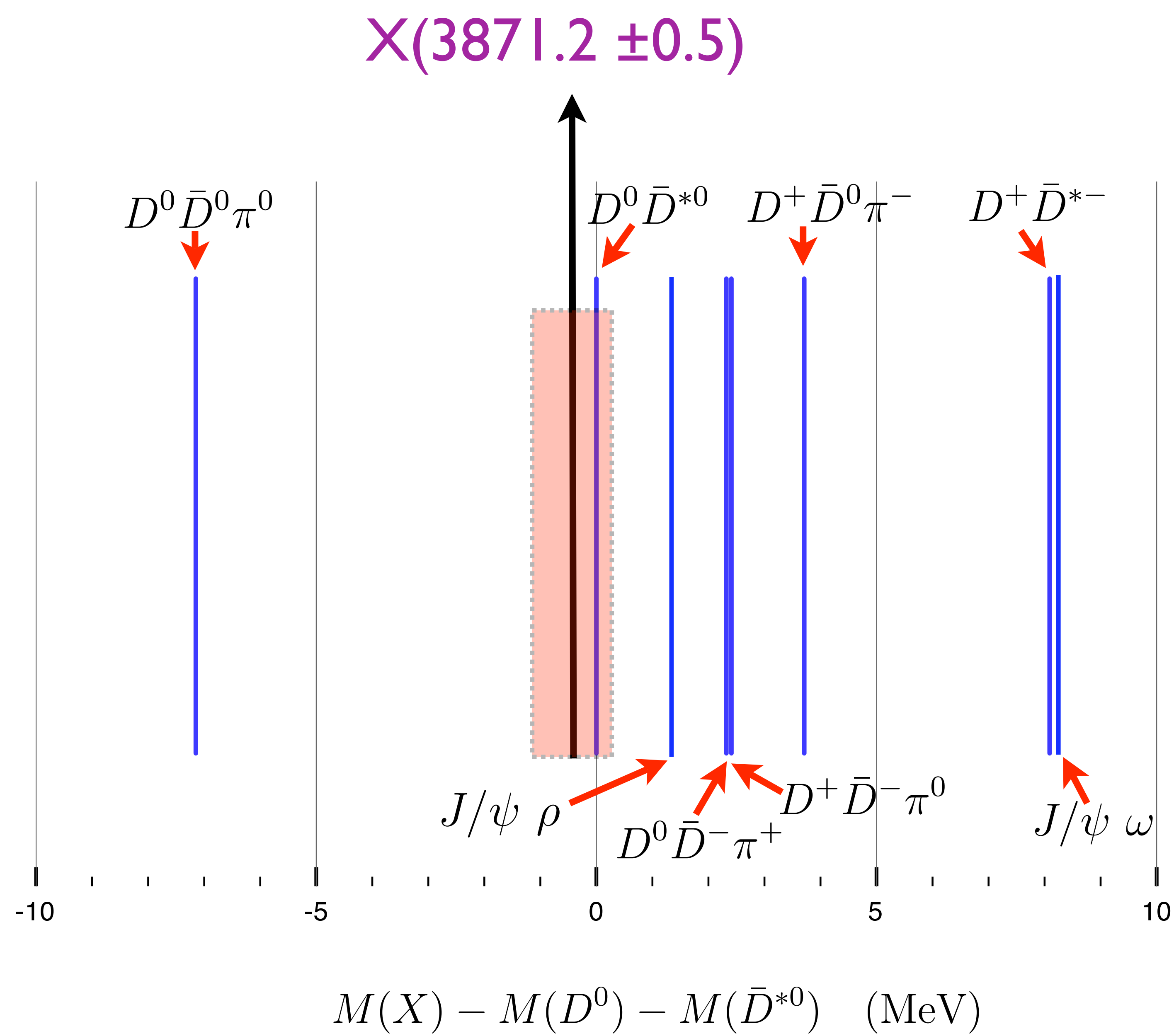


- **Use $\sim$ 220 pb^{-1} Run II Data**

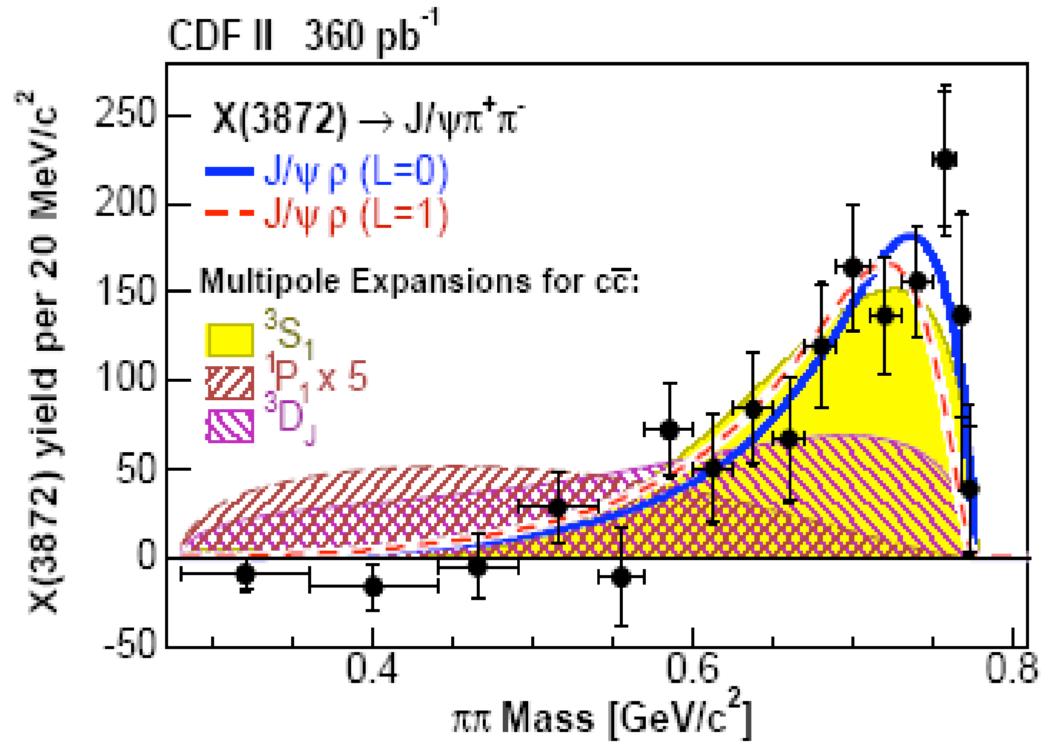




Detailed look at nearby thresholds



π π mass distribution fits ρ J/ψ (L=0)



Production rates

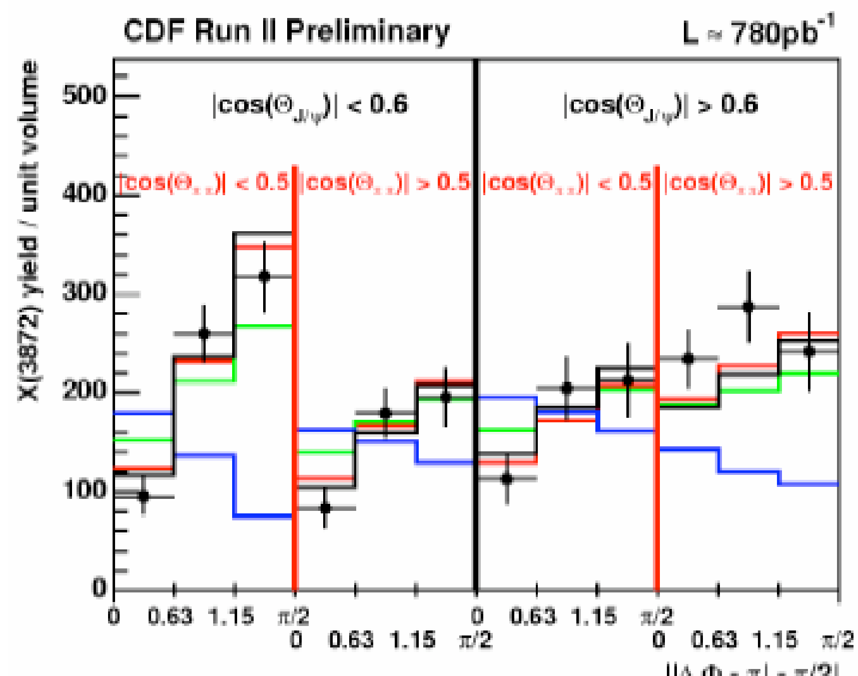
$\mathrm{J^{PC}} = 1^{++}$ Strongly favored

X(3872)
• data points

acc. corrected
prediction for

0_P^{++}
1_S^{--}
1_P^{++}
2_P^{-+}

J^{PC}	χ^2 prob.
1^{++}	27.8%
2^{-+}	25.8%
1^{--}	0.02%
2^{+-}	$5.5 \cdot 10^{-5}$
1^{+-}	$3.8 \cdot 10^{-5}$
2^{--}	$3.8 \cdot 10^{-5}$
3^{+-}	$3.8 \cdot 10^{-5}$
3^{--}	$2.4 \cdot 10^{-5}$
2^{++}	$1.1 \cdot 10^{-5}$
1^{-+}	$4.1 \cdot 10^{-6}$
0^{-+}	$3.5 \cdot 10^{-17}$
0^{+-}	$< 1 \cdot 10^{-20}$
0^{++}	$< 1 \cdot 10^{-20}$



Other decay modes:

$$\frac{X(3872) \to \text{"}\omega\text{"}\, J/\psi}{X(3872) \to \gamma J/\psi} \approx 1.0 \pm 0.4 \pm 0.3$$

Belle

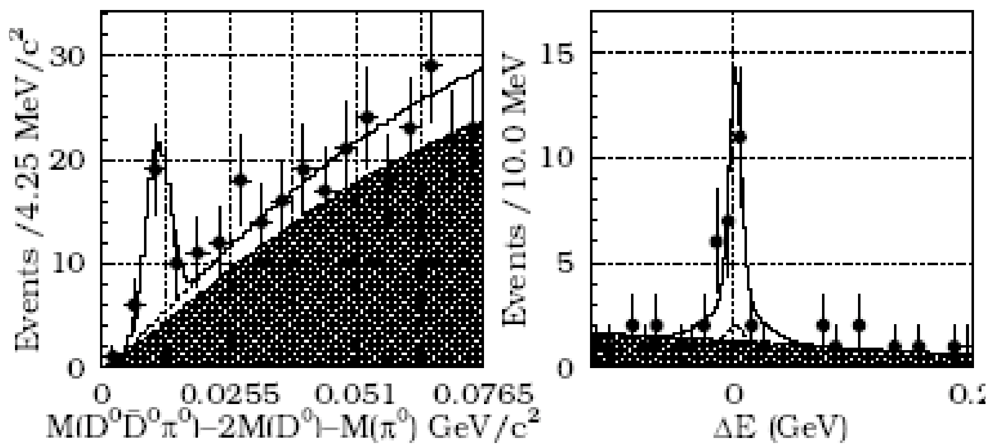
$$\frac{X(3872) \to \gamma J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 0.19 \pm 0.07$$

Belle + BaBar

Belle

$$\frac{X(3872) \to \pi^0 D^0 \bar{D}^0}{X(3872) \to \pi^+\pi^- J/\psi} \approx 10$$

$$M = 3875.4 \pm 0.7\,^{+0.7}_{-1.7} \pm 0.8\mathrm{MeV}$$



DD* "Binding Energy?":

$$M-(m_{D0}+ m_{D^*0}) = +4.3 \pm 0.7\,^{+0.7}_{-1.7} \;\; \mathrm{MeV}$$

Is the X(3872) the 2^3P_1 charmonium state ?

Mass too low:

Setting the χ'_{c2} to the observed mass and including the coupled channel effects: $M(\chi'_{c1}) = 3920$ MeV

Lattice - $M(\chi'_{c1}) = 4060\ (70)$ MeV (quenched) [Chen hep-lat/0006019]

Radiative transitions:

50% admixture of $D^0\overline{D}^0$

$$\frac{X(3872) \to \gamma\psi'}{X(3872) \to \gamma J/\psi} \approx 0.6$$

Belle + BaBar

$$\frac{X(3872) \to \gamma J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 0.19 \pm 0.07$$

TABLE VI: E1 radiative transition rates.

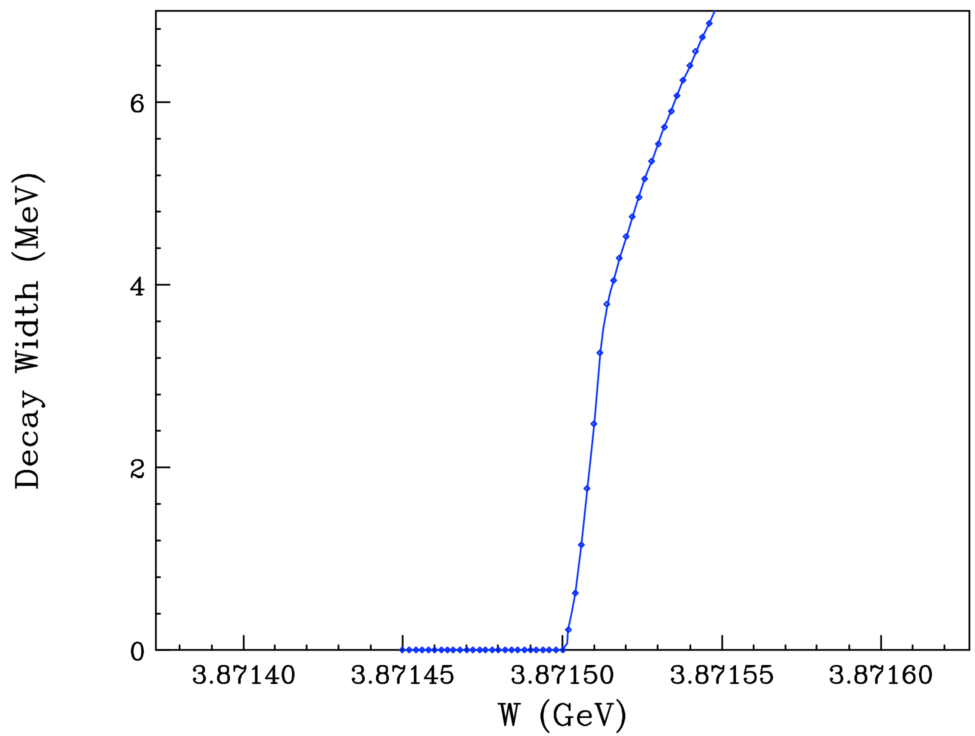
	Partial Width (keV)	
$2^3P_1(3872) \to$	$1^3D_1\,\gamma(101)$	$1^3D_2\,\gamma(41)$
model	1.05	0.2
$2^3P_1(3872) \to$	$J/\psi\,\gamma(698)$	$\psi'\,\gamma(182)$
model	34.7	21.1

Exp ratio too small

Induced isospin breaking only 8%.

Decay width grows rapidly above threshold

$$D^0\bar{D}^{0*} + D^{0*}\bar{D}^0$$



So is the X(3872) the 2^3P_1 charmonium state ?

NO (with caveats)

general form

$$|X >= cos(\alpha)|c\bar{c}(2^3P_1) > +sin(\alpha)|D^0\bar{D}^{0*} + D^{0*}\bar{D} >$$

not ruled out

Y(4260)

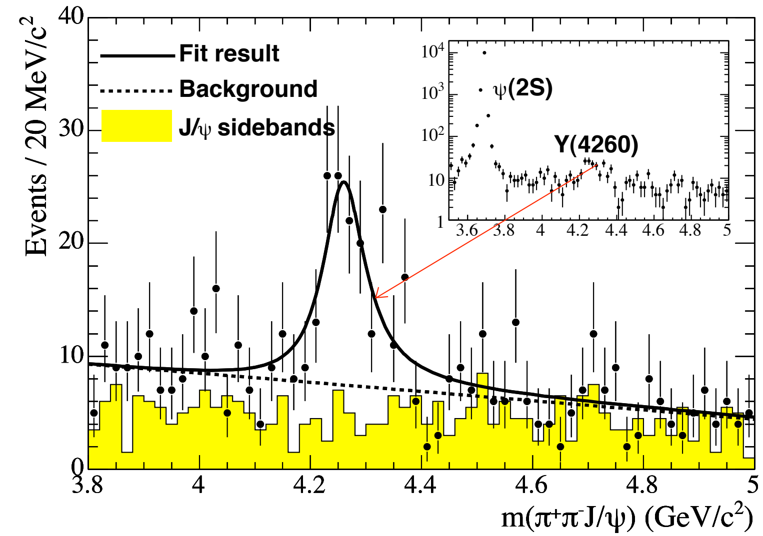
Production:

Seen by BaBar in ISR production

$J^{PC} = 1^{--}$

Exp	Mass(MeV)	Width(MeV)
BaBar	$4259\pm8^{+2}_{-6}$	$88\pm23^{+6}_{-4}$
CLEO	$4283^{+17}_{-16}\pm4$	$70^{+40}_{-25}\pm5$
Belle	$4295\pm10^{+11}_{-5}$	$133\pm26^{+13}_{-6}$

BaBar



Confirmed by CLEO and Belle

small ΔR

Decays: $\pi^+\pi^- J/\psi$ discovery mode

$\pi^0\pi^0 J/\psi$

$K^+K^- J/\psi$

CLEO

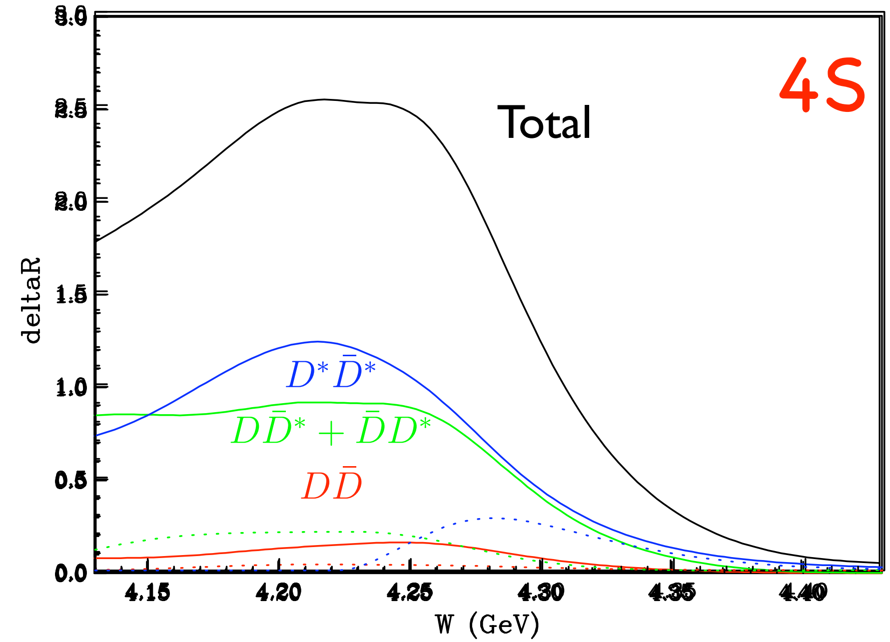
consistent with isospin zero

A charmonium state ?

4S state:

$\Delta R \sim 2.5$ for 4S at the Y(4260) mass

Ruled out

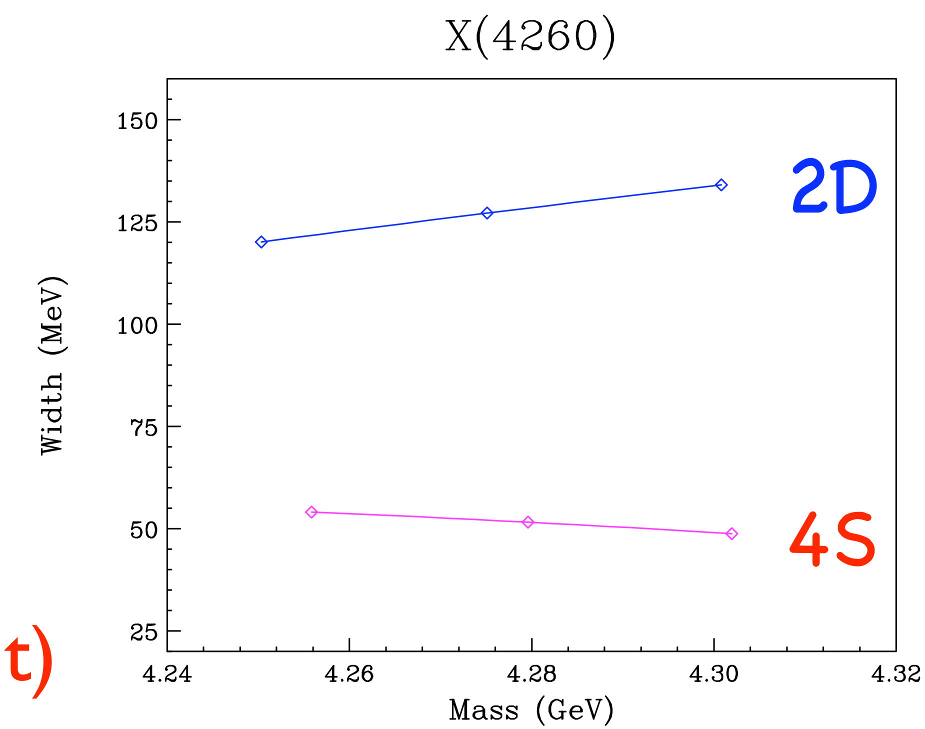


2D state:

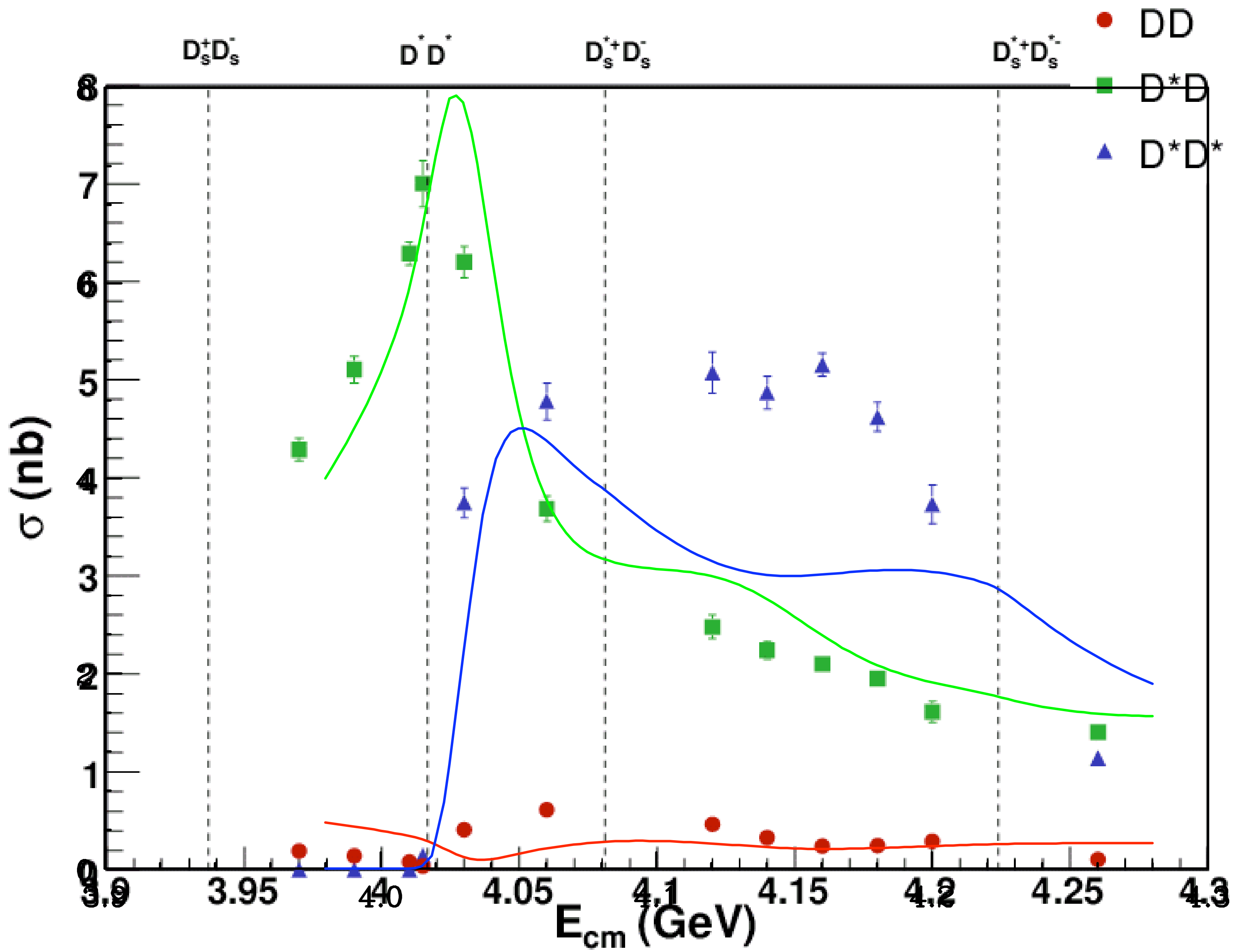
Decay widths

Already have the 2D (4160):

Ruled out (model dependent)

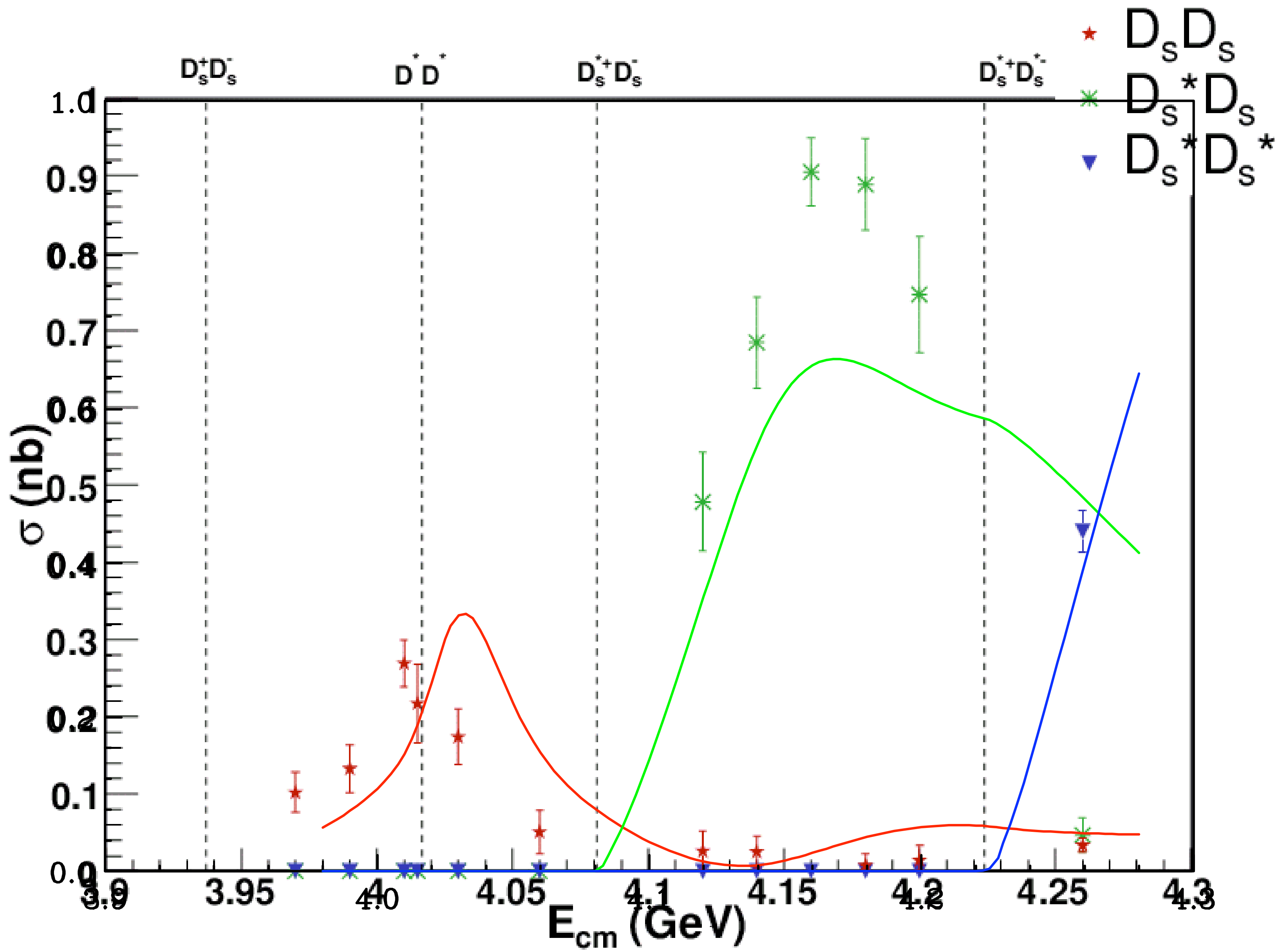


CLEO-c hep-ex/0606016



Model - Cornell Coupled Channel

CLEO-c hep-ex/0606016



Model - Cornell Coupled Channel

Y(4350)

Seen by BaBar
in the decay mode

$$\pi^+\pi^-\psi(2S)$$

Mass:

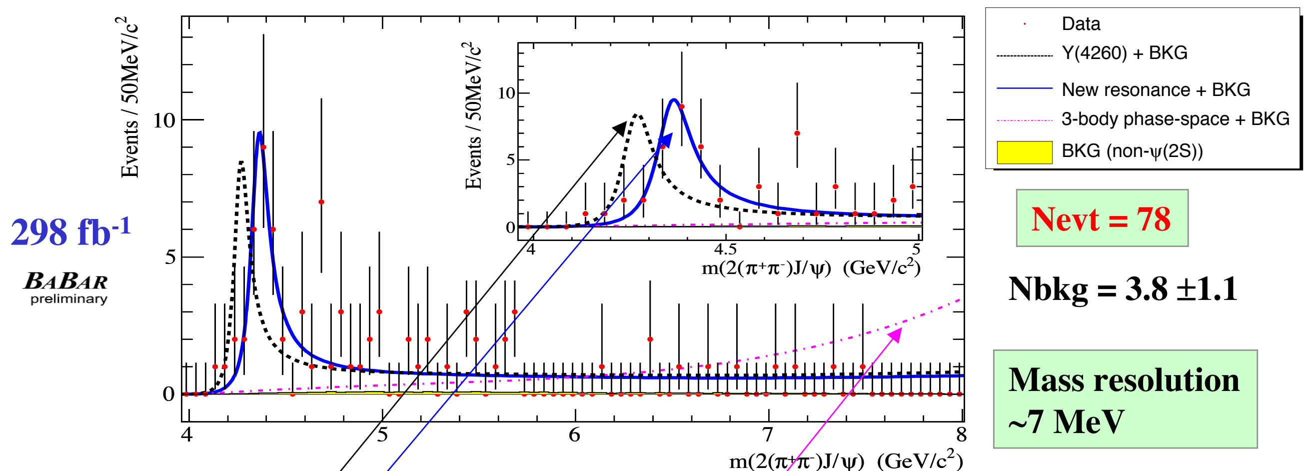
$$4354 \pm 16 \text{ MeV}$$

Width:

$$106 \pm 9 \text{ MeV}$$

...but it's not the Y(4260)...

Fit to m(2($\pi^+\pi^-$)J/ψ) to avoid combinatorics.
Try S-wave 3-body phase space, old and new resonance, **cannot find a good fit**



Incompatible with **Y(4260), ψ(4415),** or ***S*-wave 3-body phase-space** production

Assuming a **single resonance** $\Longrightarrow$ **mass=(4354±16) MeV/c^2, Γ=(106±19) MeV** (statistical errors only)

still **insufficient** to fully describe the spectrum (χ^2-prob = **1.4 ×10^{-4}**)

compared with χ^2-prob = **1.6 ×10^{-8} for Y(4260), 4.2 ×10^{-9} for ψ(4415)**

QWG06, June 27 2006 Shuwei YE 21

Confirmation needed

X, Y, Z 's Status Table

Observed	State	JPC	$c\bar{c}$	Alternative
Many	X (3872)	1++	$2\ {}^3P_1$ ✓	D D* Molecule
Belle	Z (3934)	2++	$2\ {}^3P_2$ ✓✓✓	
Belle	Y (3940)	JP+	?	
Belle	X (3943)	0-+	$3\ {}^1S_0$ ✓✓	
Babar CLEO Belle	Y (4260)	1--	$4\ {}^3S_1$ ✗ $2\ {}^3D_1$	Hybrid
Babar	Y (4350)	1--	$4\ {}^3S_1$ ✗ $2\ {}^3D_1$	?

Issues and Opportunities

Options for X(3872) (225 papers)

$D^0\bar{D}^{0*}$ molecule:

Tornqvist (8-03, 2-04); Close and Page (9-03); Pakvasa and Suzuki (9-03); Voloshin (9-03, 8-04, 9-05, 5-06); Wong (11-03); Braaten and Kusunoki (11-03; 2-04; 12-04, 6-05, 7-05, 9-06); Swanson (11-03, 6-04, 10-04); Braaten, Kusunoki, and Nussinov (4-04); Kalashnikova (6-05); AlFiky, Gabbiani, and Petrov (6-05); El-Hady (3-06), Chiu and Hsieh (3-06); Zhang, Chiang, Shen and Zou (4-06); Melikhov and Stech (6-06)

threshold cusp:

Bugg (10-04)

tetraquark: $(\bar{c}\bar{q})_3(qc)_{\bar{3}}$

Vijande, Fernandez, and Valcarce (7-04); Maiani, Piccinini, Polosa, and Riquer (12-04); Ishida, Ishida and Maeda (9-05); Ebert, Faustov and Galkin (12-05); Karliner and Lipkin (1-06); Chiu and Hsieh (3-06)

tetraquark: $(\bar{c}c)_8(\bar{q}q)_8$

Hogassen, Richard and Sorba (11-05); Buccella, Hogassen, Richard and Sorba (8-06)

hybrid: $(\bar{c}gc)$

Close and Page (9-03); Li (10-04)

In a two body system with short range interactions and an S-wave bound state sufficiently close to threshold

Universal properties depending only on the large scattering length (a)

Braaten and Hammer [cond-mat/0410417]

This applies to the X(3872)

Braaten and Kusunoki

If $a > 0$ one bound state

$$\frac{1}{a} = \gamma_r + i\gamma_i$$

$$\mathrm{E_X} = \gamma_r^2/(2\mu)$$

$$\Gamma_\mathrm{X} = 2\gamma_r\gamma_i/\mu$$

$$\mu = \frac{M(D^0)M(D^{0*})}{M(D^0)+M(D^{0*})}$$

$$\psi(r) = \frac{\exp(-\gamma_r r)}{r}$$

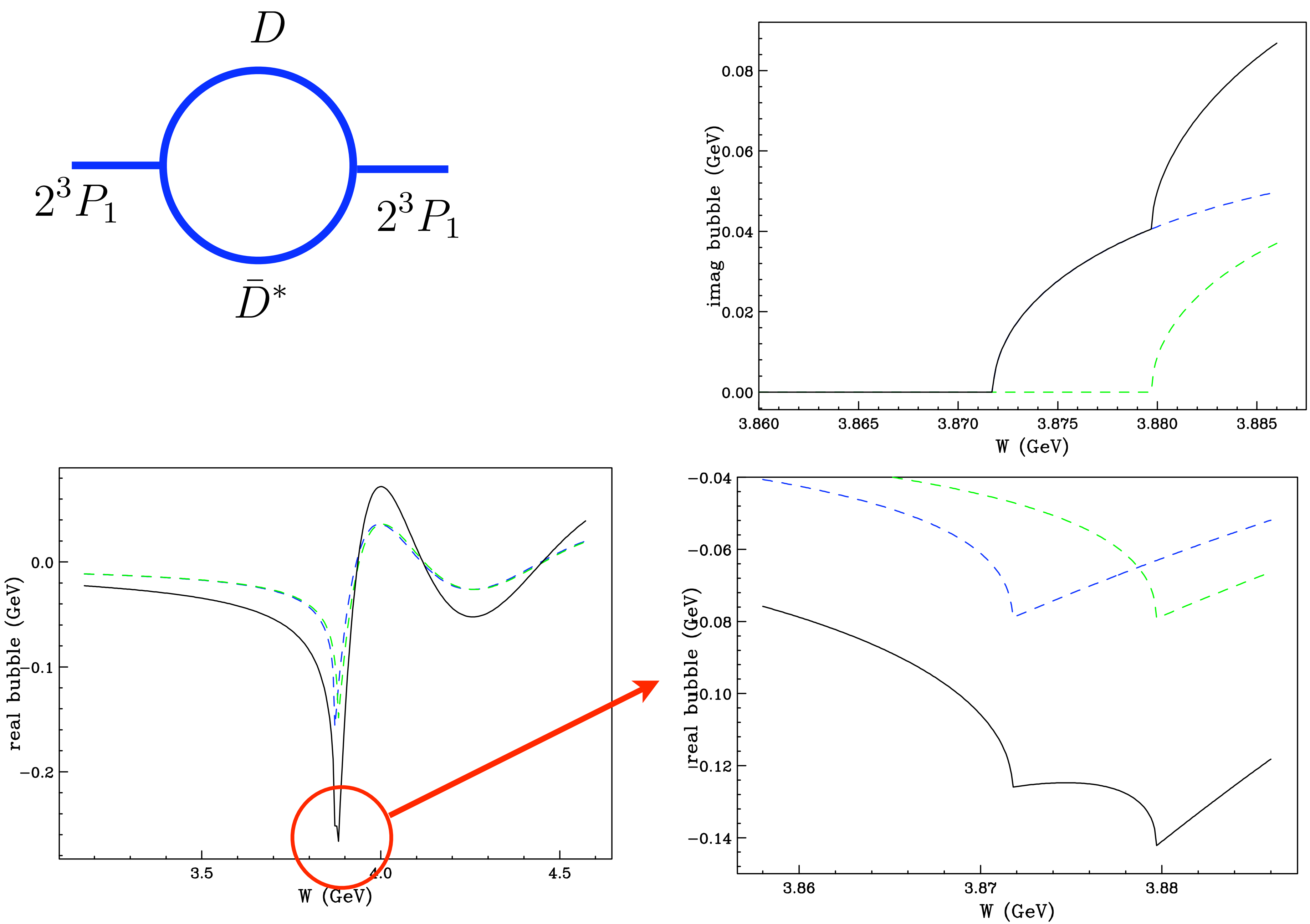
$$\sigma(E) = \frac{\pi}{\gamma_r^2 + (\gamma_i + \sqrt{2\mu E})^2}$$

Very large average separation between the charm quark and antiquark

> 7 fm

Since this behavior is universal it gives no insight into how the bound state forms

Strong S-wave coupling for 2P state

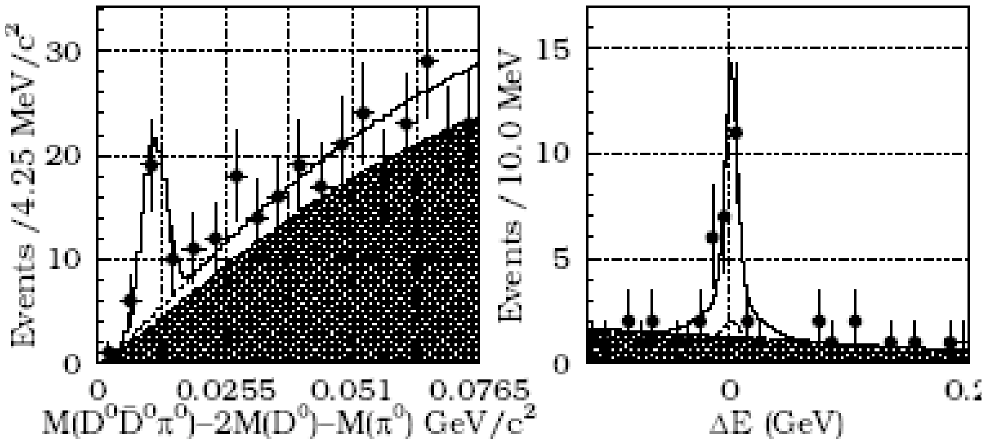


Belle

For molecular interpretation:

$$\sigma(E) = \frac{\pi}{\gamma_r^2 + (\gamma_i + \sqrt{2\mu E})^2}$$

Fit?



Lattice calculation:

Chiu and Hsieh [hep-lat/0603207]

$$\begin{aligned}
M_1 &= \frac{1}{\sqrt{2}}\{(\bar{\mathbf{q}}\gamma_i\mathbf{c})(\bar{\mathbf{c}}\gamma_5\mathbf{q}) - (\bar{\mathbf{c}}\gamma_i\mathbf{q})(\bar{\mathbf{q}}\gamma_5\mathbf{c})\} \quad ✓\\
M_2 &= (\bar{\mathbf{q}}\gamma_5\gamma_i\mathbf{q})(\bar{\mathbf{c}}\mathbf{c})\\
M_3 &= \frac{1}{\sqrt{2}}\{(\bar{\mathbf{q}}\gamma_5\gamma_i\mathbf{c})(\bar{\mathbf{c}}\mathbf{q}) + (\bar{\mathbf{c}}\gamma_5\gamma_i\mathbf{q})(\bar{\mathbf{q}}\mathbf{c})\}\\
M_4 &= (\bar{\mathbf{c}}\gamma_5\gamma_i\mathbf{c})(\bar{\mathbf{q}}\mathbf{q})
\end{aligned}$$

✓ signal

M = 3890±30 MeV

V dependence
fits single meson

$$X_4(x) = \frac{1}{\sqrt{2}}\left\{(\mathbf{q}^T C\gamma_i\mathbf{c})_{xa}(\bar{\mathbf{q}}C\gamma_5\bar{\mathbf{c}}^T)_{xa} - (\bar{\mathbf{q}}C\gamma_i^T\bar{\mathbf{c}}^T)_{xa}(\mathbf{q}^T C\gamma_5\mathbf{c})_{xa}\right\} \quad ✓$$

Much work remains - quenched; single lattice spacing

Options for Y(4260) (62 papers)

hybrid: $(\bar{c}gc)$

Close and Page (7-05); Kou and Pene (7-05); Zhu (7-05); Juge, O'Cais, Oktay, Peardon and Ryan (10-05); Luo and Liu (12-05); Chiu and Hsieh (12-05); Swanson (9-05, 1-06); Barnes (10-05); Eichten, Lane and Quigg (11-05); S. Godfrey (5-06); Buisseret and Mathieu (7-06);

threshold effect:

Beveren and Rupp (5-06); Rosner (8-06)

tetraquark: $(\bar{c}q)_1(\bar{q}c)_1$, $(\bar{c}\bar{q})_3(qc)_{\bar{3}}$, or $(\bar{c}c)_8(\bar{q}q)_8$

Liu, Zeng and Li, (7-05); Bigi, Maiani, Piccinini, Polosa and Riquer (10-5); Yuan, Wang and Mo (11-05); Ebert, Faustov and Galkin (12-05); Maiani, Riquer, Piccinini and Polosa (3-06); Stancu (7-06); Cui, Chen, Deng and Zhu (7-06); Buccella, Hogassen, Richard and Sorba (8-06)

Y(4260)

Molecular state - Unlikely

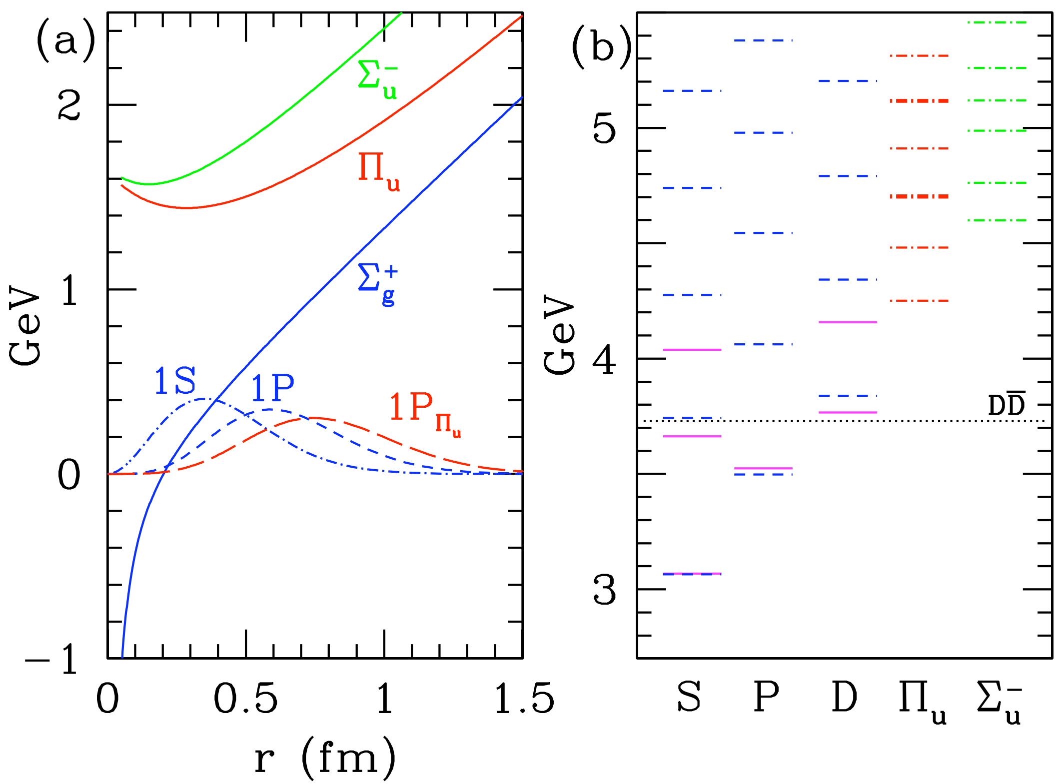
Channel	Threshold Energy	Width	
$D_s^{*+} D_s^{*-}$	4223.8	-	P wave
$D\bar{D}_1(3/2^+)$	4286.5	20.3(1.7)	D wave
$D\bar{D}_1(1/2^+)$	4306(32)	329(76)	S wave
$D\bar{D}_2(3/2^+)$	4327.5	43.8(2.0)	D wave
$D^*\bar{D}_0(1/2^+)$	4315(36)	276(66)	D wave

Threshold effects - Needs more modeling

Hybrid - Attractive

Close and Page [hep-ph/0507199]

Zhu [hep-ph/0507025]



Charmonium

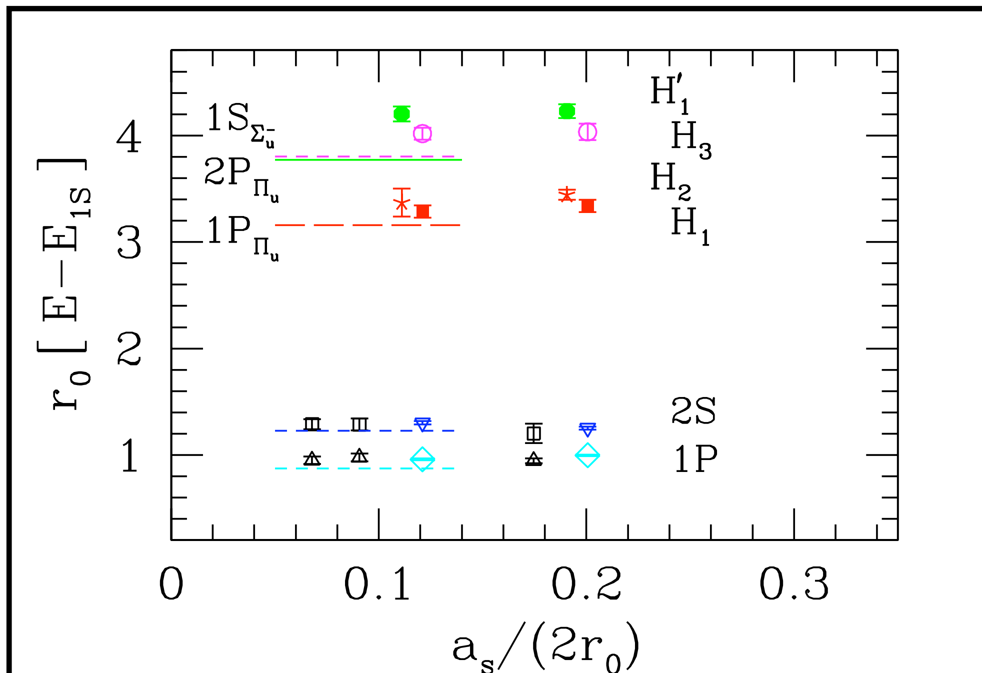
Juge, Kuti, Morningstar [nucl-th/0307116]

Expect triplet partners

J^{PC}		Degeneracies	Operator
0^{-+}	S wave	1^{--}	$\chi^{\dagger}\,(\boldsymbol{D}^2)^p\,\psi$
1^{+-}	P wave	$0^{++}, 1^{++}, 2^{++}$	$\chi^{\dagger}\,\boldsymbol{D}\,\psi$
1^{--}	H_1 hybrid	$0^{-+}, 1^{-+}, 2^{-+}$	$\chi^{\dagger}\,\boldsymbol{B}(\boldsymbol{D}^2)^p\,\psi$
1^{++}	H_2 hybrid	$0^{+-}, 1^{+-}, 2^{+-}$	$\chi^{\dagger}\,\boldsymbol{B}\times\boldsymbol{D}\,\psi$
0^{++}	H_3 hybrid	1^{+-}	$\chi^{\dagger}\,\boldsymbol{B}\cdot\boldsymbol{D}\,\psi$

Quenched Spectrum

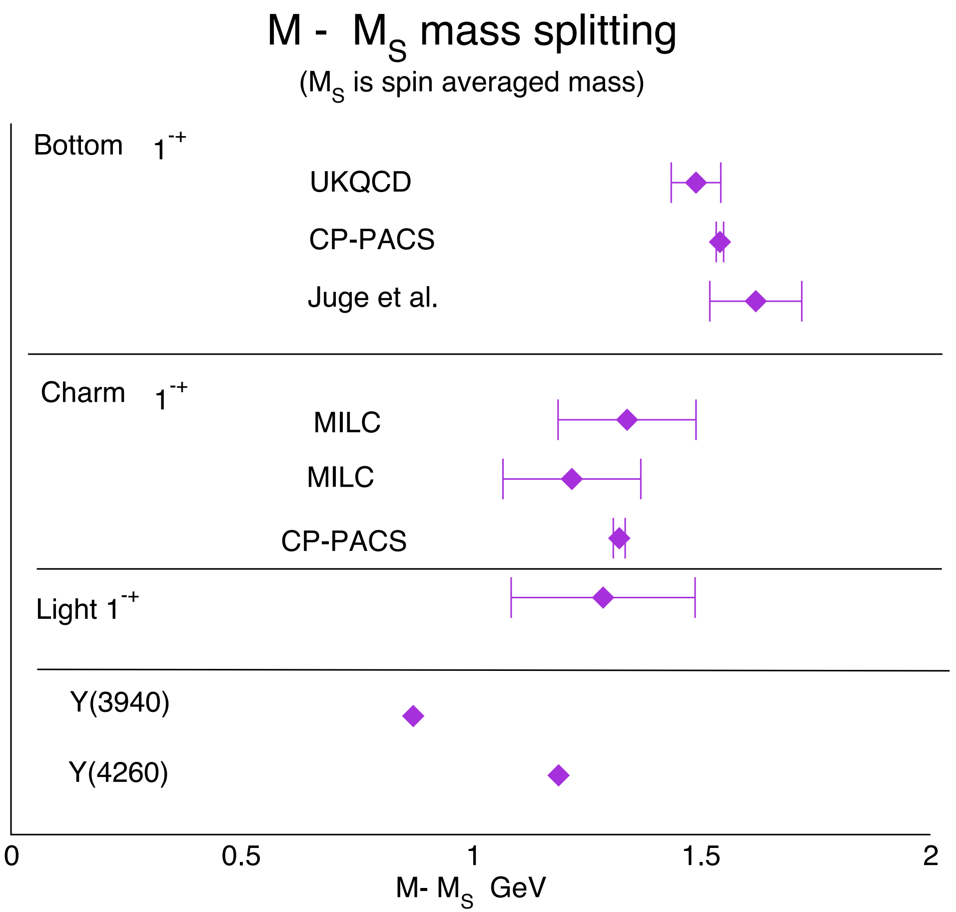
How many narrow?



Lattice calculations:

$$M(1^{-+}) = M(1^{--}) \text{ (leading order in } 1/m_c)$$

McNeile review
ICHEP 2006



Two direct calculations: Y(4260):

Chiu and Hsieh [hep-lat/0512029]

consistent with D^*D_{p0} molecule: 4238(31)(57)
not hybrid ~4500

Luo and Liu [hep-lat/0512044]

consistent with hybrid: 4379(149)

Analog States Above Bottom Threshold

NRQCD and HQS allow detailed predictions for the scaling behavior in heavy quark mass.

- $X_c(3872)$ -> $X_b(10604)$
  New state present for threshold effect, molecular and other four quark explanations.
  Isospin violation likely small
  Decay modes modified: B^* -> B γ, nearest $^3P_1(b\bar{b})$ state below threshold, etc.

- $Y_c(4260)$ -> Y_b -- Mass depends on interpretation
  Hybrid - Scaling of SE with effective potential fixed
  Threshold state - shifts with threshold values.

- Observable at hadron colliders ?

SUMMARY

- Narrow heavy-heavy states:
  - The 2^3P_2 and 3^1S_0 charmonium states likely found.
  - All three remaining low-lying L=2 charmonium states are narrow: $1^3D_2, 1^1D_2, 1^3D_3$
  - A proper calculation for the masses and decay rates of these states must include the large effects from nearby (real/virtual) open charm decay channels.
  - Detailed predictions for masses, mixings and decays using the CCCM give sensible results and can be used to guide the identification of other missing charmonium states.

- QCD in all its richness:

  The two states: X(3872) and Y(4260) do not fit gracefully in any simple charmonium interpretation.

- If X(3872) is a molecular state:

  Possible analogy states in $b\bar{b}$ system

  Possible analogy states near other S-wave thresholds.

- If Y(4260) is a hybrid state:

  0^{-+}, 1^{-+} and 2^{-+} nearby states.

  Need lattice calculations.

- Need improved theoretical tools to study QCD at threshold.

Backup Slides

Heavy-Light Predictions

TABLE I: The heavy-light spectrum compared to experiment. We report the difference between the excited state masses and the ground state (D or B) in each case. We have assumed that $\Delta M(m_c) = \Delta M(m_b) = \Delta M(\infty) = 349$ MeV.

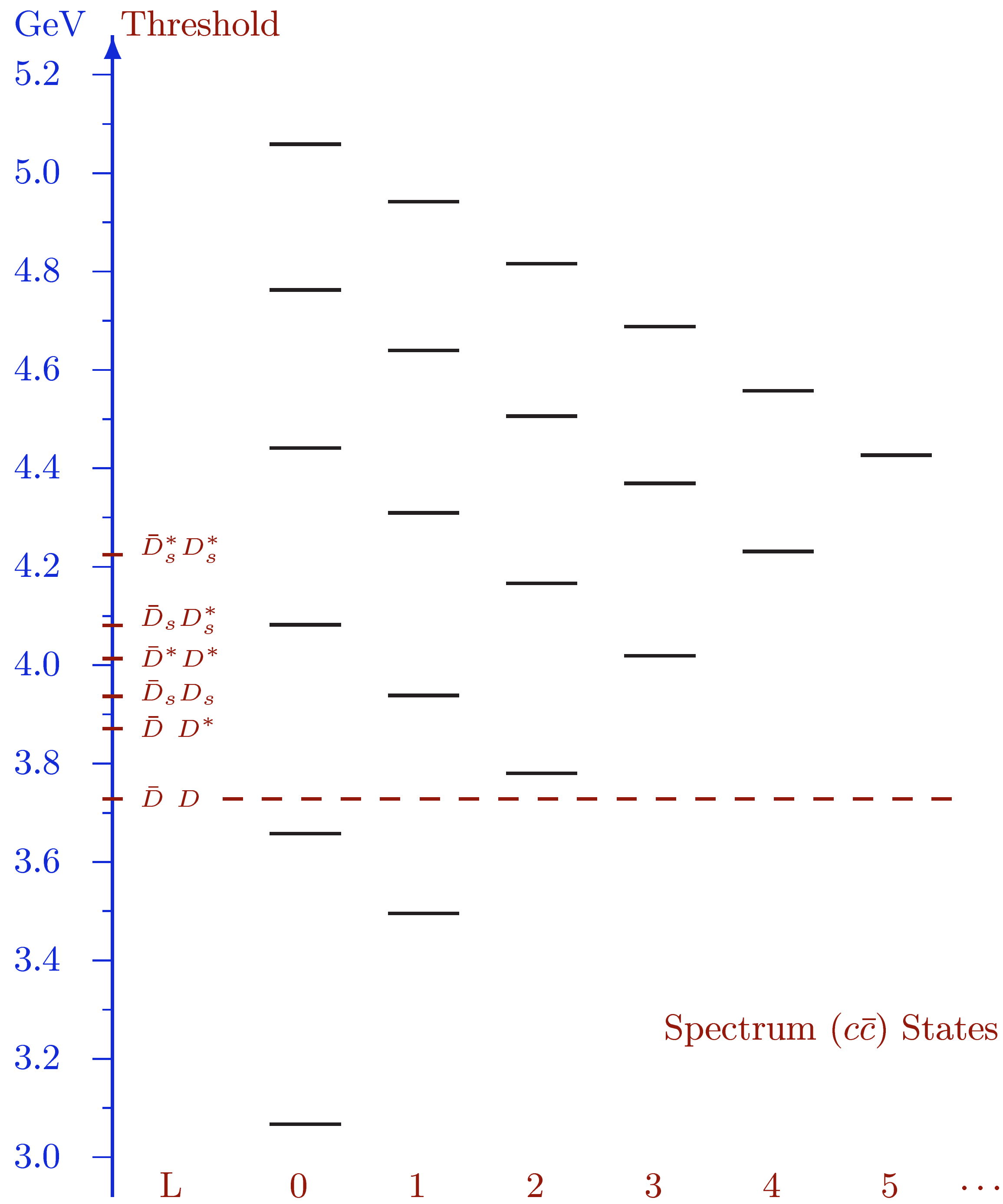
charmed meson masses [MeV]			bottom meson masses [MeV]		
	model	experiment		model	experiment
$D^{*0} - D^0$	142 [a]	142.12 ± 0.07	$B^{*0} - B^0$	46 [a]	45.78 ± 0.35
$D^{*+} - D^+$	141 [a]	140.64 ± 0.10	$B^{*+} - B^+$	46 [a]	45.78 ± 0.35
$D_s^{*+} - D_s^+$	144 [a]	143.8 ± 0.41	$B_s^{*+} - B_s^+$	47 [a]	47.0 ± 2.6
$D^0(0^+) - D^0$	349		$B^0(0^+) - B^0$	349	
$D^+(0^+)^-D^+$	349		$B^+(0^+)^-B^+$	349	
$D_s^+(0^+)^-D_s^+$	349 [a]	349 ± 1.3 [b]	$B_s^+(0^+)^-B_s^+$	349	
$D^0(1^+) - D^0(0^+)$	142		$B^0(1^+) - B^0(0^+)$	46	
$D^+(1^+)^-D^+(0^+)$	141		$B^+(1^+)^-B^+(0^+)$	46	
$D_s^+(1^+)^-D_s^+(0^+)$	144		$B_s^+(1^+)^-B_s^+(0^+)$	47	

[a] Experimental input to model parameters fit. [b] BaBar result [1].

W. Bardeen, C. Hill, E.E. [Phys. Rev. D68, 054024 (2003)]

TABLE II: The predicted hadronic and electromagnetic transistion rates for narrow $j_l^P = 1/2^-(1S)$ and $j_l^P = 1/2^+(1P)$ heavy-light states. "Overlap" is the reduced matrix element overlap integral; "dependence" refers to the sensitive model parameters, as defined in the text. We take $G_A = 1$ and extract g_A from a fit to the D^{+*} total width. Note that the $\overline{c}s$ transitions are sensitive to $r_{\overline{c}s}$; if we implement the observed ratio of branching fractions $(D_s(1^-) \to D_s(0^-)\pi^0)/\Gamma(D_s(1^-) \to D_s(0^-)\gamma) = 0.062 \pm 0.026$ then the E1 radiative transitions for the $\overline{c}s$ system should be reduced by a factor of ~ 3

system	transition	Q(keV)	overlap	dependence	Γ (keV)	exptl BR
$(c\overline{u})$	$1^- \to 0^- + \gamma$	137	0.991	$r_{\overline{c}u}$	33.5	$(38.1 \pm 2.9)\%$
	$1^- \to 0^- + \pi^0$	137		g_A	43.6	$(61.9 \pm 2.9)\%$
	total				77.1	
$(c\overline{d})$	$1^- \to 0^- + \gamma$	136	0.991	$r_{\overline{c}d}$	1.63	$(1.6 \pm 0.4)\%$
	$1^- \to 0^- + \pi^0$	38		g_A	30.1	$(30.7 \pm 0.5)\%$
	$1^- \to 0^- + \pi^+$	39		g_A	65.1	$(67.7 \pm 0.5)\%$
	total				96.8	96 ± 22
$(c\overline{s})$	$1^- \to 0^- + \gamma$	138	0.992	$r_{\overline{c}s}$	0.43	$(94.2 \pm 2.5)\%$
	$1^- \to 0^- + \pi^0$	48		$g_A\delta_{\eta\pi 0}$	0.0079	$(5.8 \pm 2.5)\%$
	total				0.44	
$(c\overline{s})$	$0^+ \to 1^- + \gamma$	212	2.794	$r_{\overline{c}s}$	1.74	
	$0^+ \to 0^- + \pi^0$	297		$G_A\delta_{\eta\pi 0}$	21.5	
	total				23.2	
$(c\overline{s})$	$1^+ \to 0^+ + \gamma$	138	0.992	$r'_{\overline{c}s}$	2.74	
	$1^+ \to 0^+ + \pi^0$	48		$g_A\delta_{\eta\pi 0}$	0.0079	
	$1^+ \to 1^- + \gamma$	323	2.638	$r_{\overline{c}s}$	4.66	
	$1^+ \to 0^- + \gamma$	442	2.437	$r_{\overline{c}s}$	5.08	
	$1^+ \to 1^- + \pi^0$	298		$G_A\delta_{\eta\pi 0}$	21.5	
	$1^+ \to 0^- + 2\pi$	221		$g_A\delta_{\sigma_1\sigma_3}$	4.2	
	total				38.2	
$(b\overline{u})$	$1^- \to 0^- + \gamma$	46	0.998	$r_{\overline{b}u}$	0.78	
	total				0.78	
$(b\overline{d})$	$1^- \to 0^- + \gamma$	46	0.998	$r_{\overline{b}d}$	0.24	
	total				0.24	
$(b\overline{s})$	$1^- \to 0^- + \gamma$	47	0.998	$r_{\overline{b}s}$	0.15	
	total				0.15	
$(b\overline{s})$	$0^+ \to 1^- + \gamma$	293	2.536	$r_{\overline{b}s}$	58.3	
	$0^+ \to 0^- + \pi^0$	297		$G_A\delta_{\eta\pi 0}$	21.5	
	total				79.8	
$(b\overline{s})$	$1^+ \to 0^+ + \gamma$	47	0.998	$r'_{\overline{b}s}$	0.061	
	$1^+ \to 1^- + \gamma$	335	2.483	$r_{\overline{b}s}$	56.9	
	$1^+ \to 0^- + \gamma$	381	2.423	$r_{\overline{b}s}$	39.1	
	$1^+ \to 1^- + \pi^0$	298		$G_A\delta_{\eta\pi 0}$	21.5	
	$1^+ \to 0^- + 2\pi$	125		$g_A\delta_{\sigma_1\sigma_3}$	0.12	
	total				117.7	


GeV
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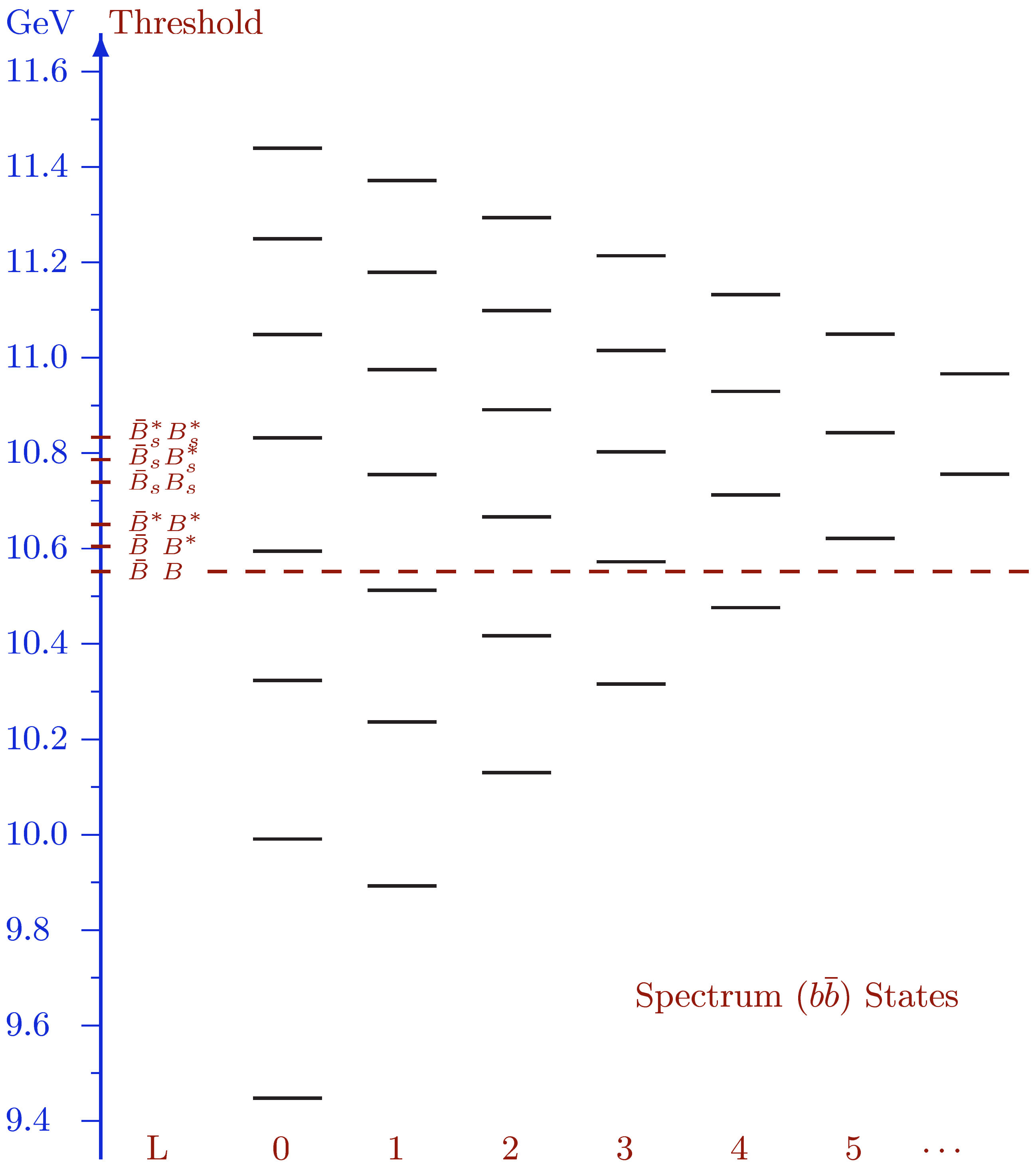
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
$\bar{D}_s^* D_s^*$
$\bar{D}_s D_s^*$
$\bar{D}^* D^*$
$\bar{D}_s D_s$
$\bar{D}\ D^*$
$\bar{D}\ D$
Spectrum $(c\bar{c})$ States
L
0
1
2
3
4
5
$\cdots$


GeV
Threshold
11.6
11.4
11.2
11.0
10.8
10.6
10.4
10.2
10.0
9.8
9.6
9.4
$\bar{B}^*_s B^*_s$
$\bar{B}_s B^*_s$
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Spectrum $(b\bar{b})$ States
L
0
1
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4
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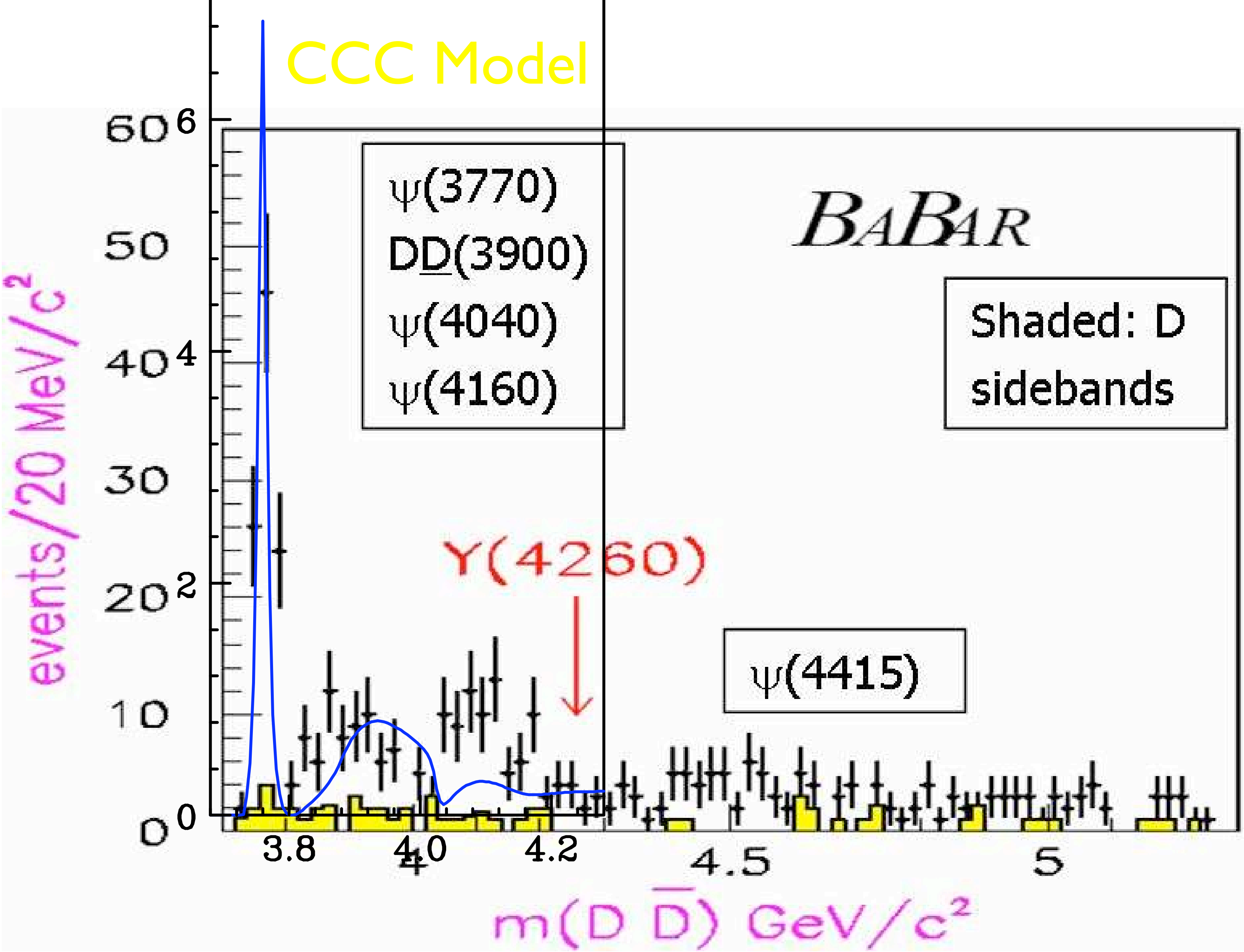
$\cdots$



$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi)} < 7.6 \ @ \ 95\% \text{ C.L.}$$

Look for other 1D states and DDbar threshold